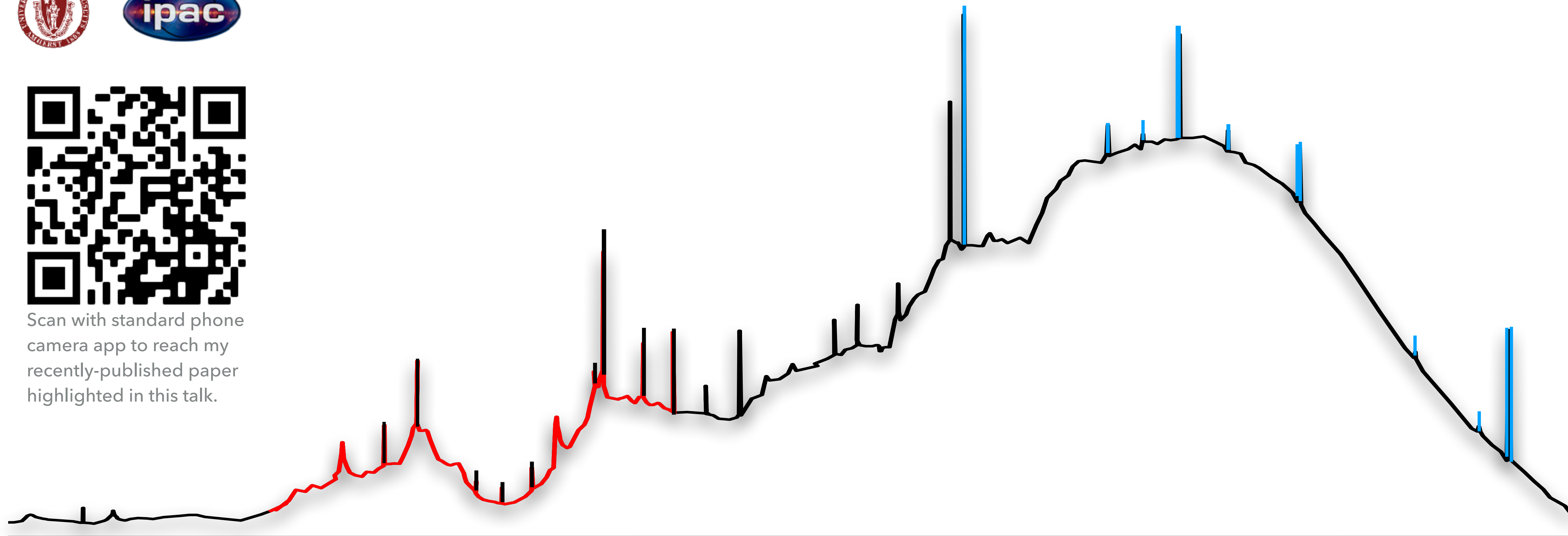




Scan with standard phone camera app to reach my recently-published paper highlighted in this talk.

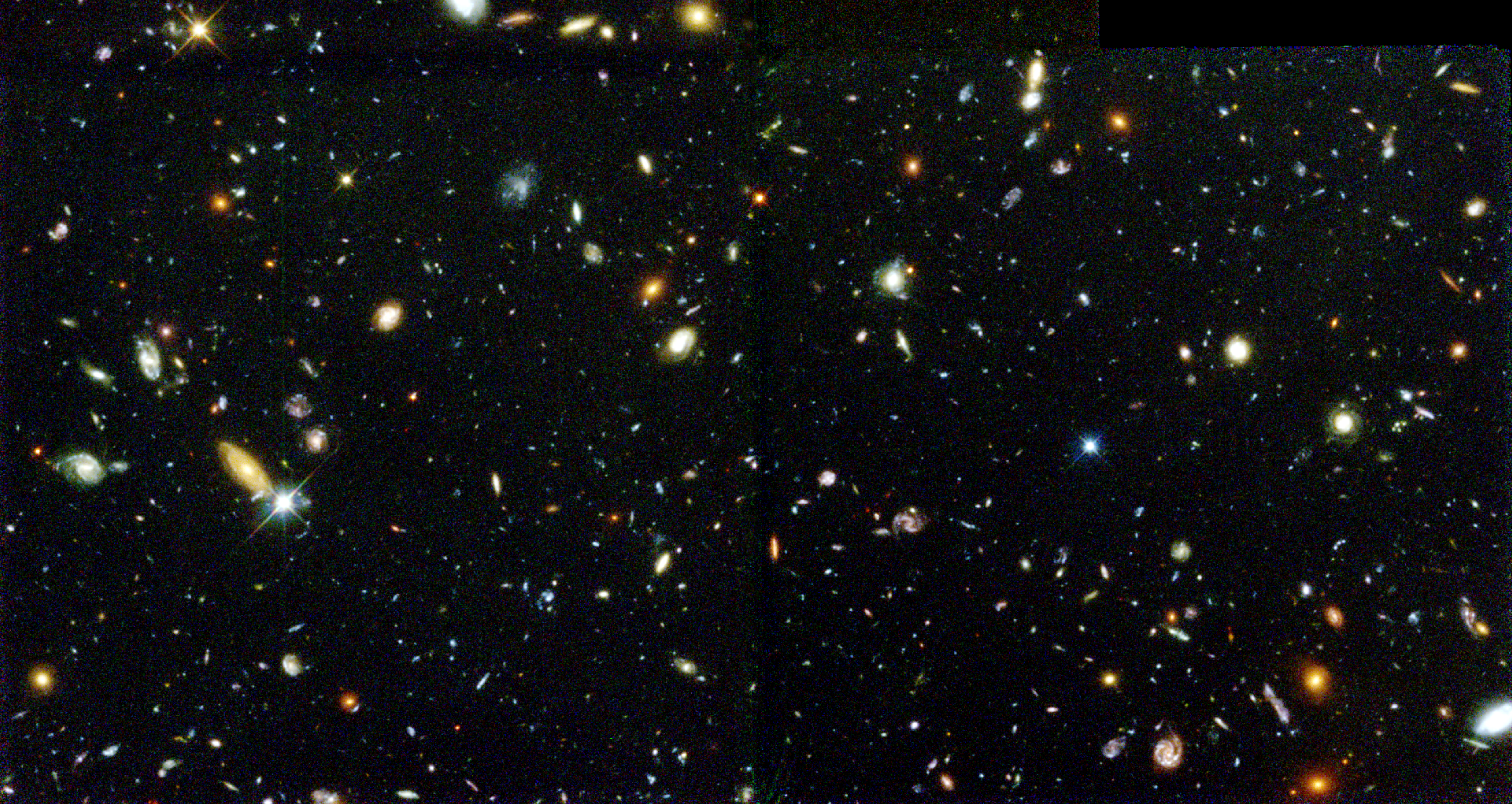


HEATING AND COOLING IN THE INTERSTELLAR MEDIUM OF DUSTY, STAR-FORMING GALAXIES

In collaboration with: **Alexandra Pope** (UMass, thesis advisor), **Lee Armus** (IPAC, VGF advisor), T. Díaz-Santos, V. Charmandaris, H. Inami, Y. Song, A.S. Evans, R-R. Chary, M.E. Dickinson, A. Kirkpatrick

OUTLINE

- ▶ Introduction and background
 - ▶ Why study dusty galaxies?
 - ▶ Heating and cooling in the ISM
- ▶ The interstellar medium of local dusty galaxies
- ▶ The interstellar medium of dusty galaxies at high-redshift

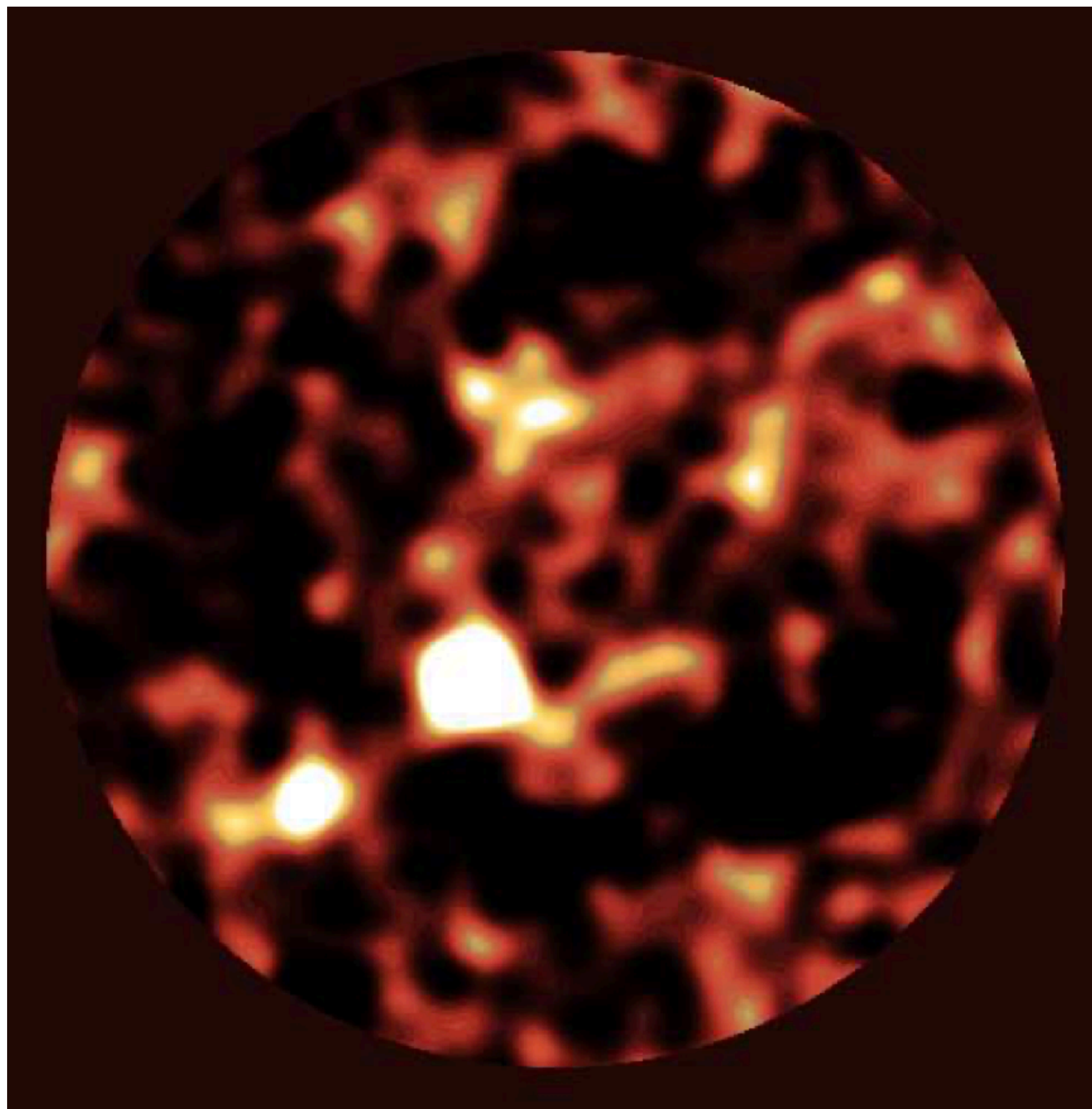


Hubble Deep Field

ST ScI OPO January 15, 1996 R. Williams and the HDF Team (ST ScI) and NASA

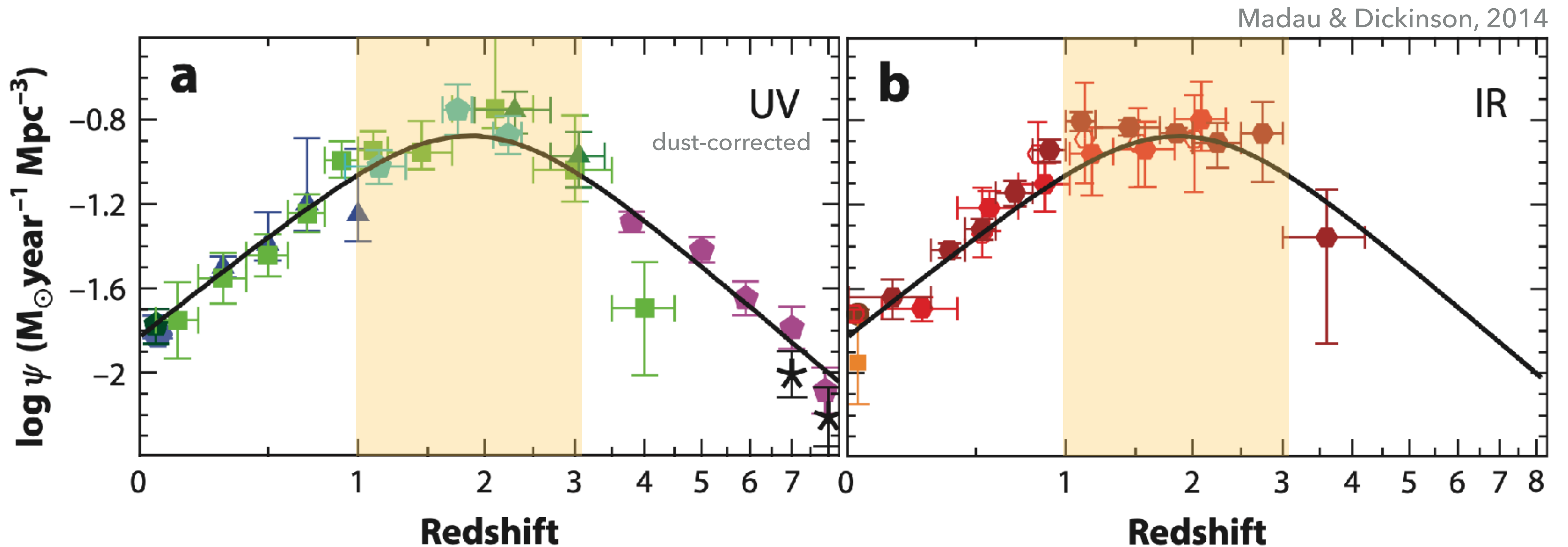
HST

WFPC2



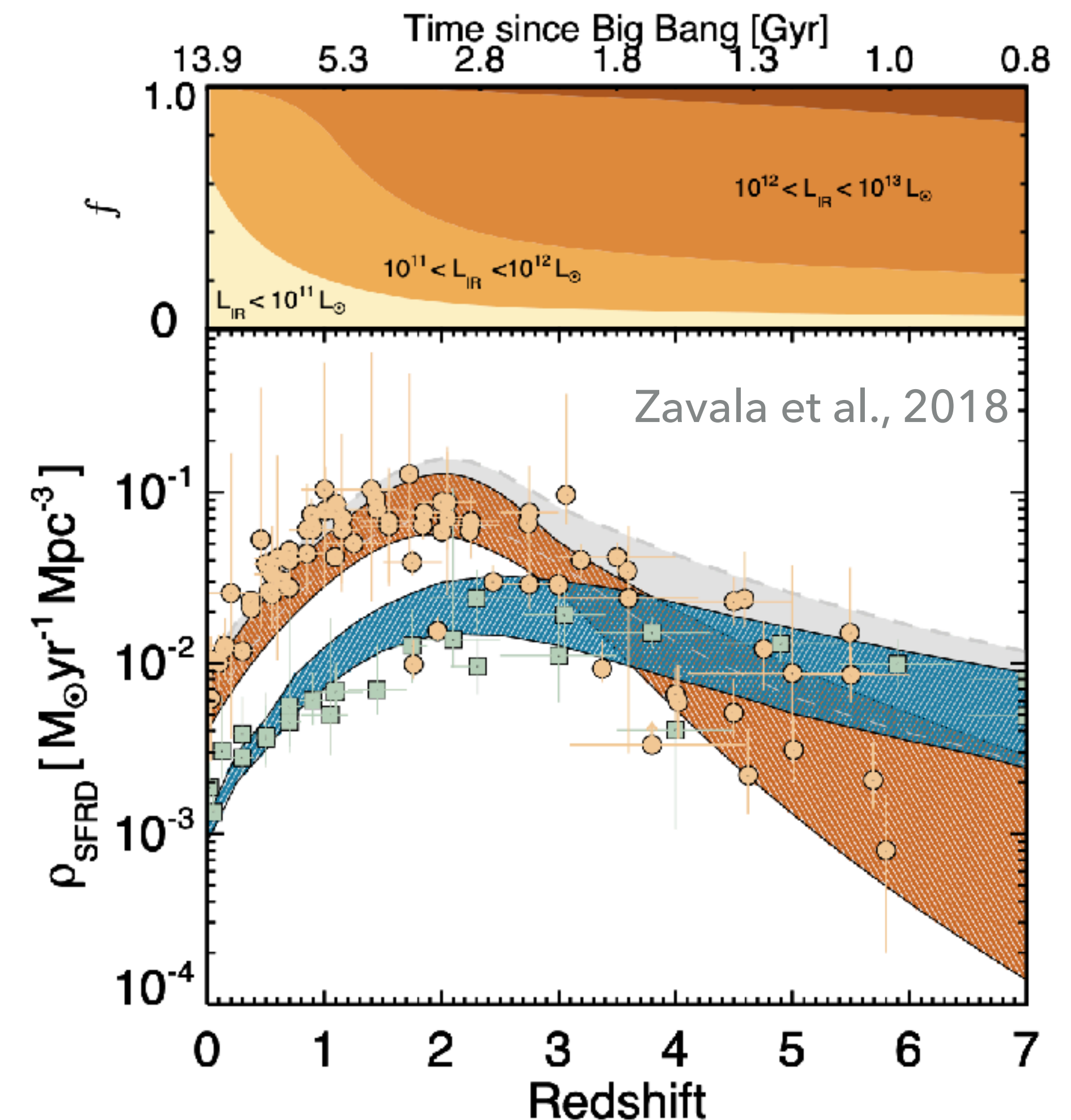
850 μm image of the HDF, Hughes et al., 1998

A “COSMIC NOON” – THE PEAK IN THE STAR-FORMATION RATE DENSITY

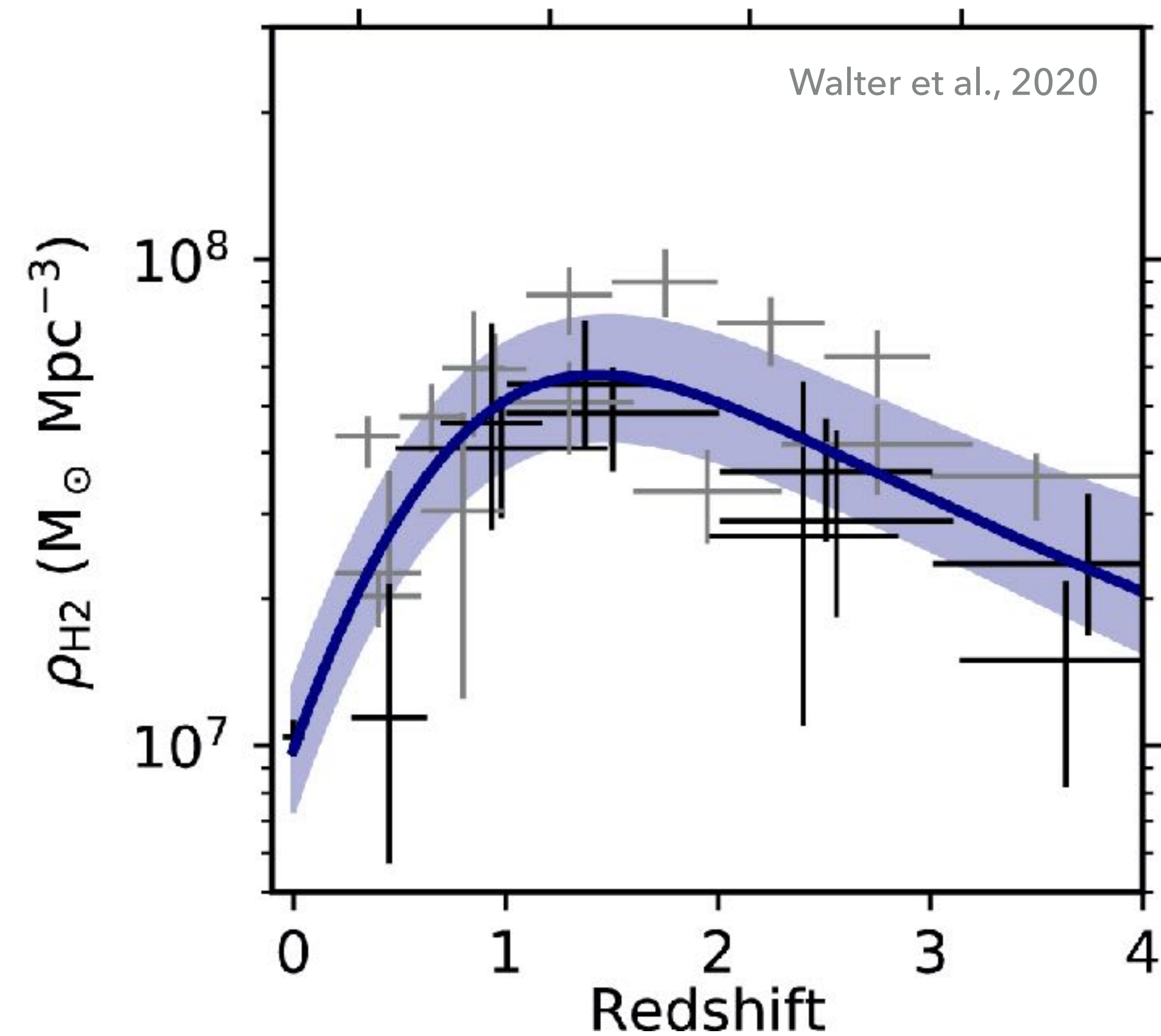
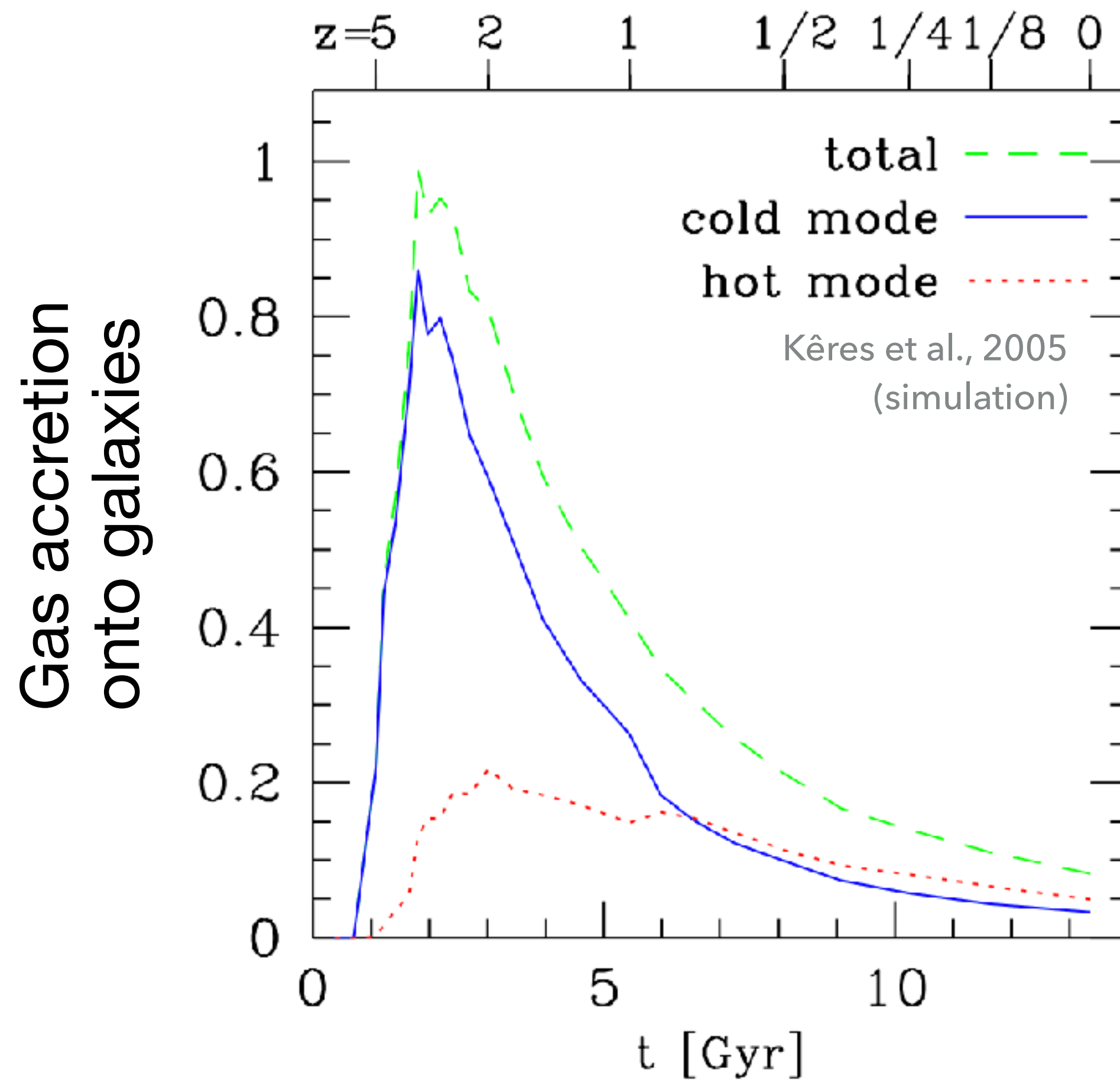


A “COSMIC NOON” – THE PEAK IN THE STAR-FORMATION RATE DENSITY

- ▶ The star-formation rate density of the Universe peaked about 3-5 Gyr after the Big Bang ($z \sim 2$).
- ▶ Most of the star-formation at $z < 3$ is obscured by dust.
- ▶ Most of the dust-obscured star-formation happens in massive, IR-luminous galaxies ($L_{\text{IR}} > 10^{11} L_{\odot}$).

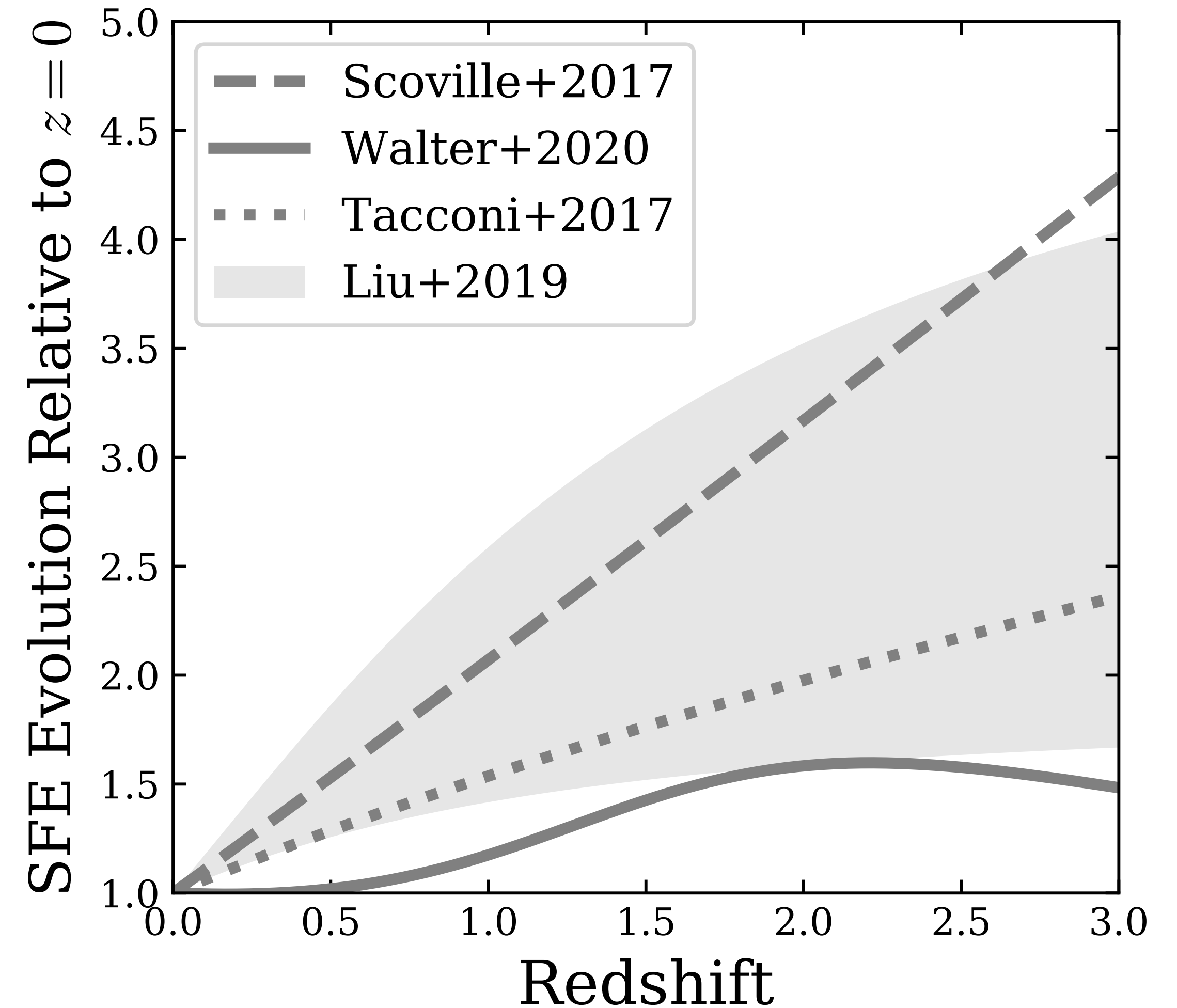


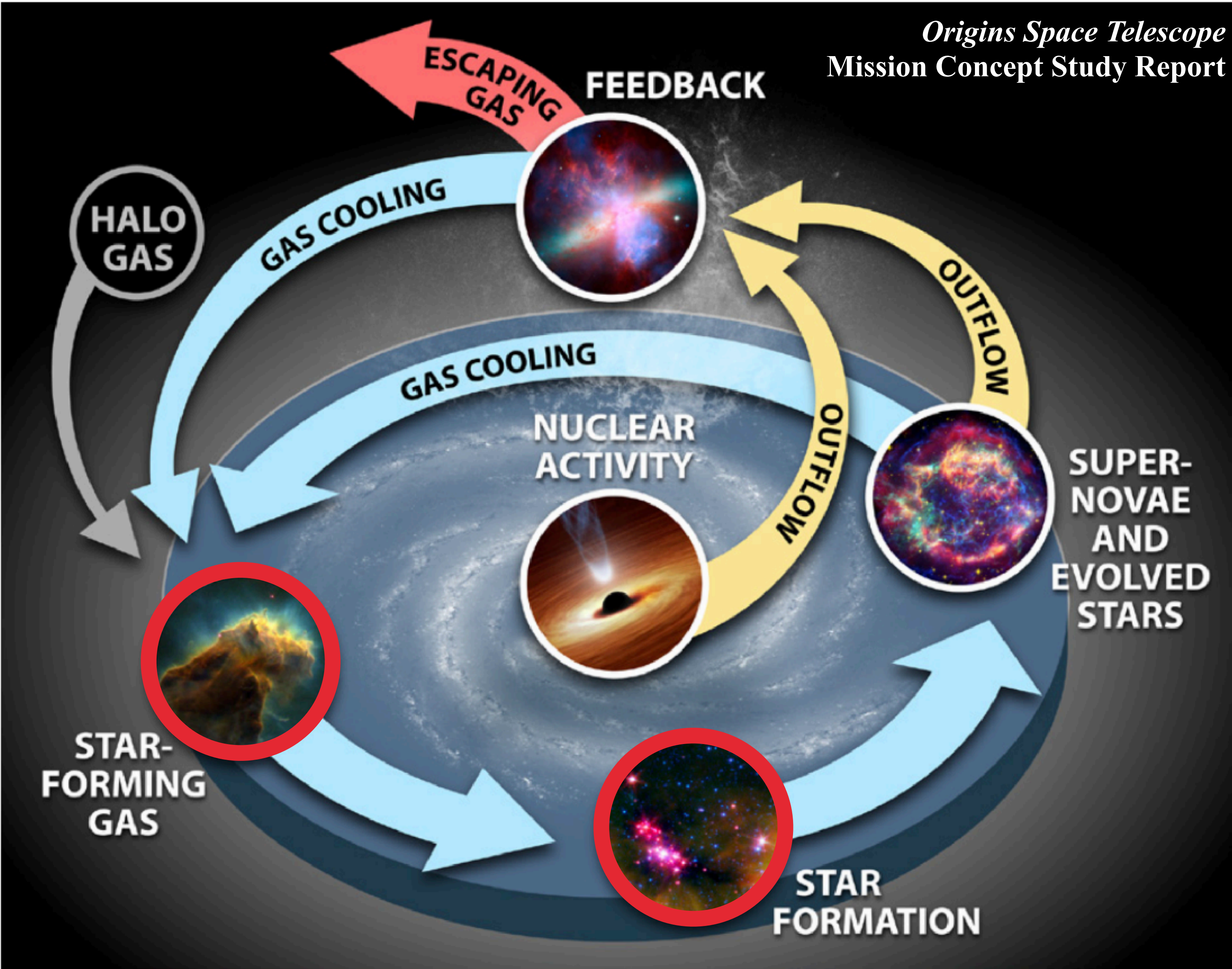
WHY DO HIGH-REDSHIFT GALAXIES HAVE HIGH STAR-FORMATION RATES?



WHY DO HIGH-REDSHIFT GALAXIES HAVE HIGH STAR-FORMATION RATES?

- ▶ Star-formation efficiency (SFE)
 $\equiv \text{SFR}/M_{\text{H}_2}$
- ▶ The SFE could be very important to the evolution of galaxies, or not.
- ▶ What can change the efficiency of star-formation in dusty galaxies?

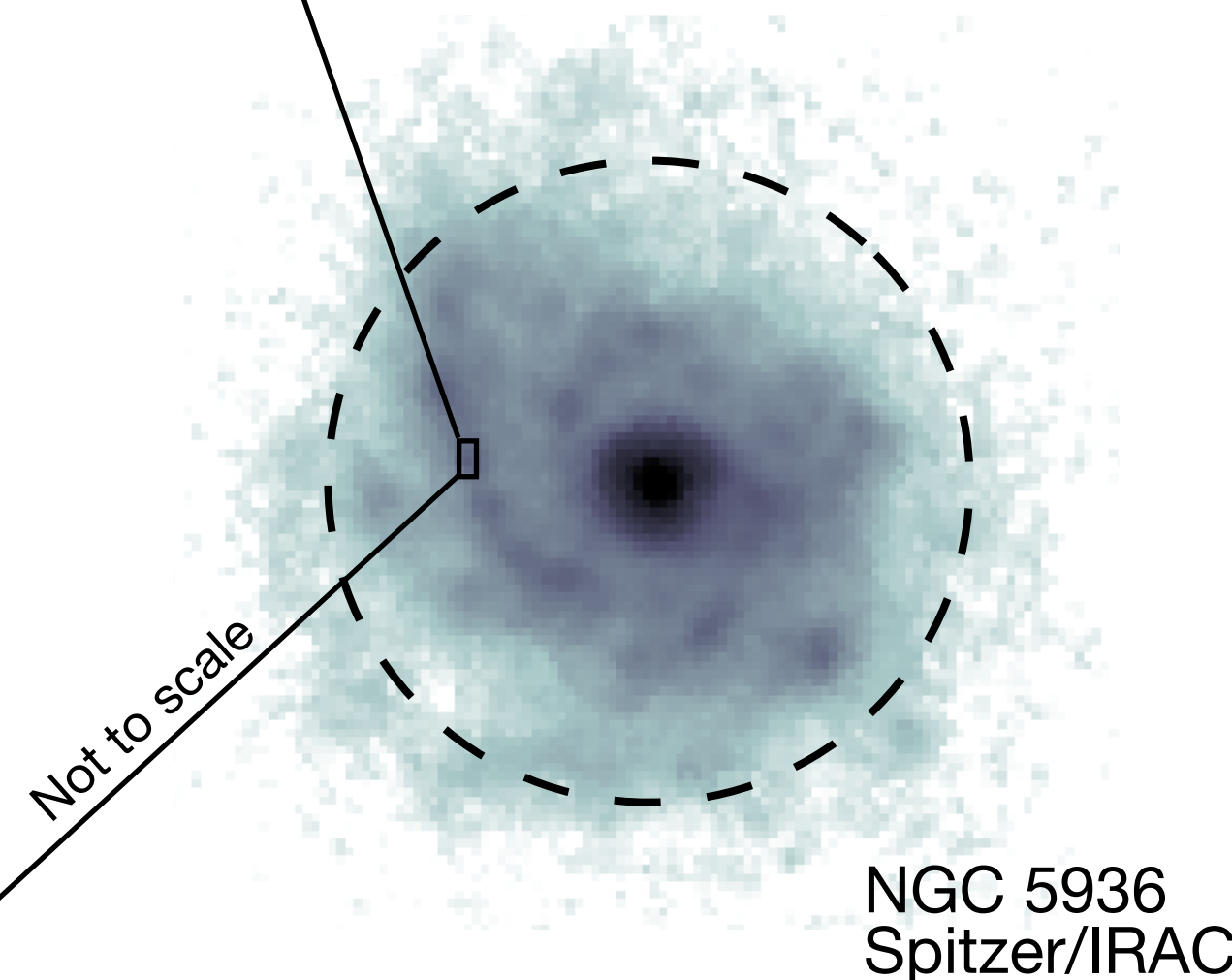




PHOTODISSOCIATION REGIONS (PDR) IN STAR-FORMING GALAXIES



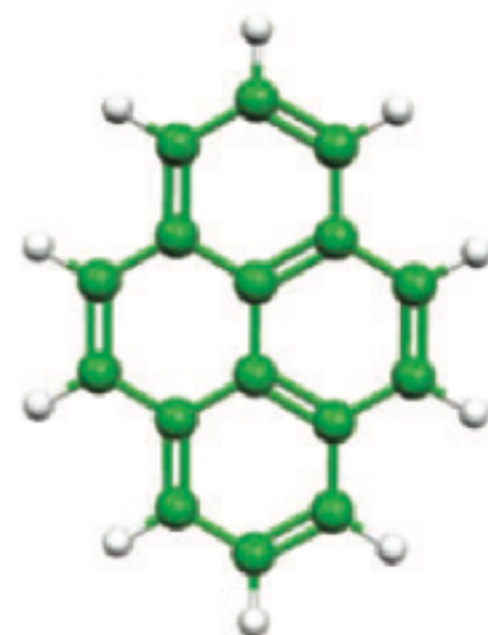
- ▶ **Gas Cooling:** IR fine-structure line cooling dominated by [C II], [O I] and [Si II] emission.
- ▶ **Gas Heating:** Dominated by the photoelectric effect off of small dust grains, PAHs. Observed in bright mid-IR bands with e.g., *Spitzer*.



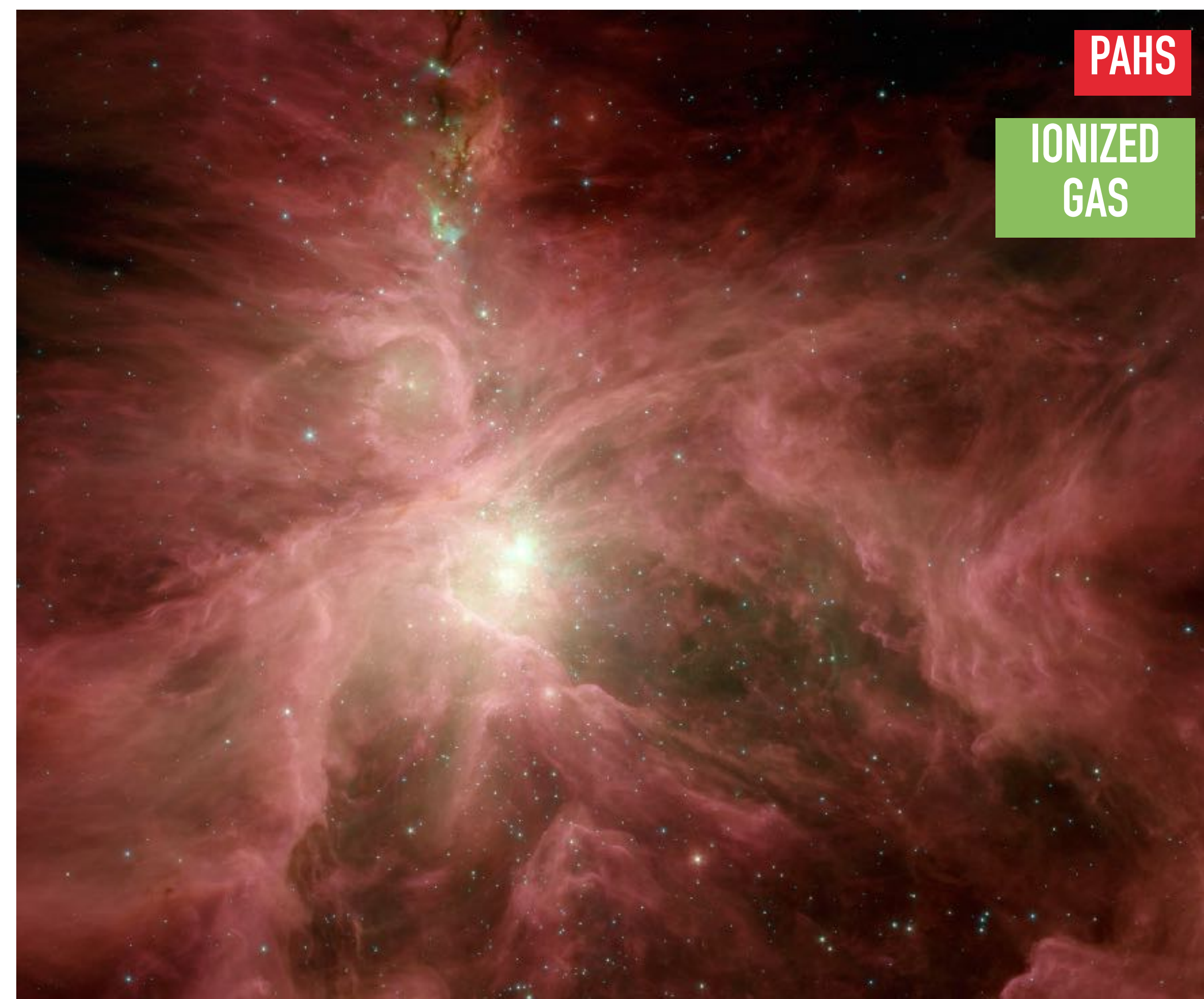
Galaxy-integrated measurements of atomic and molecular lines test heating and cooling of the ISM in galaxies.

POLYCYCLIC AROMATIC HYDROCARBONS (PAHS)

- ▶ Dominate the heating of neutral gas in PDRs.
- ▶ PAH emission is bright in star-forming regions, and in star-forming galaxies

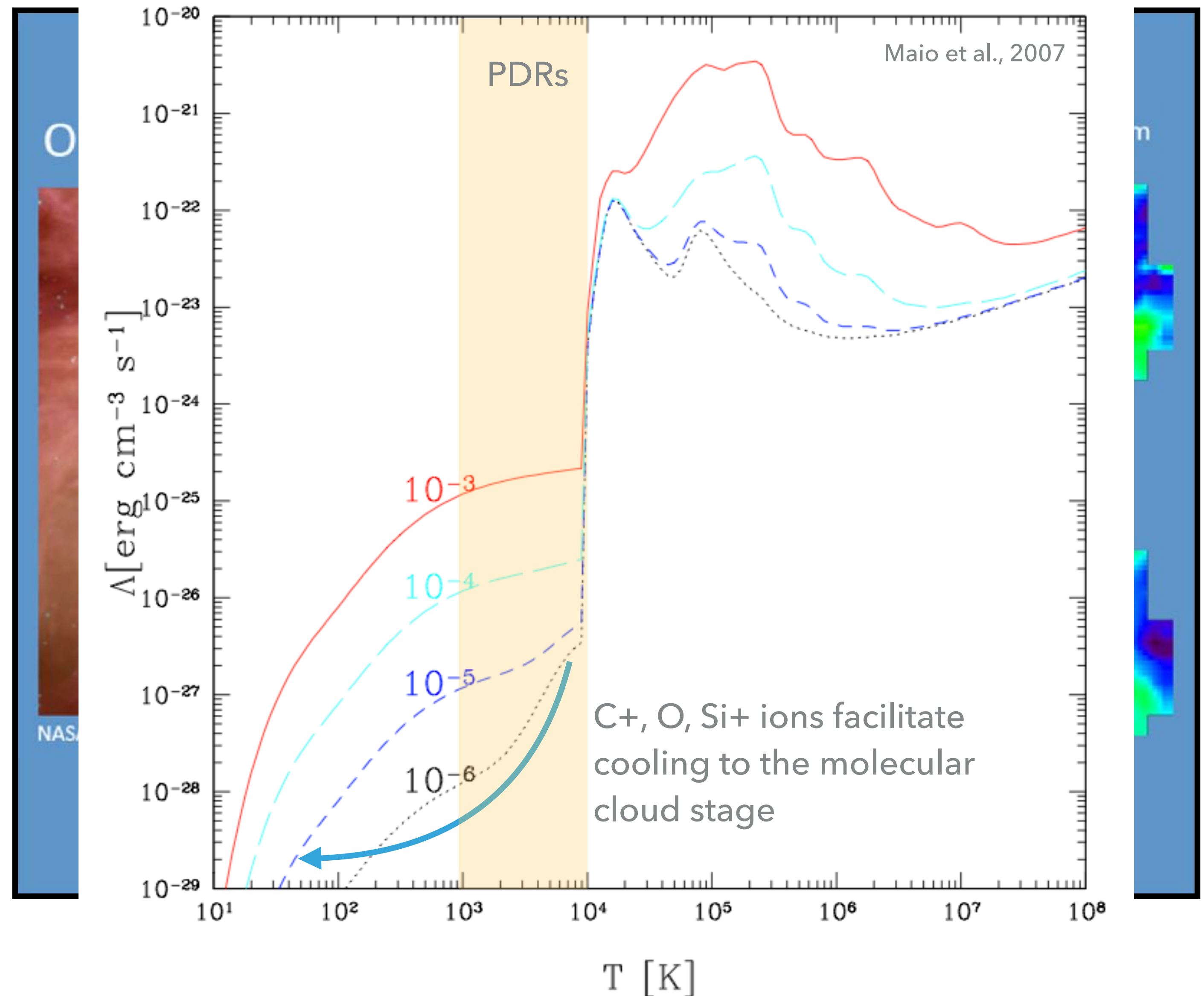


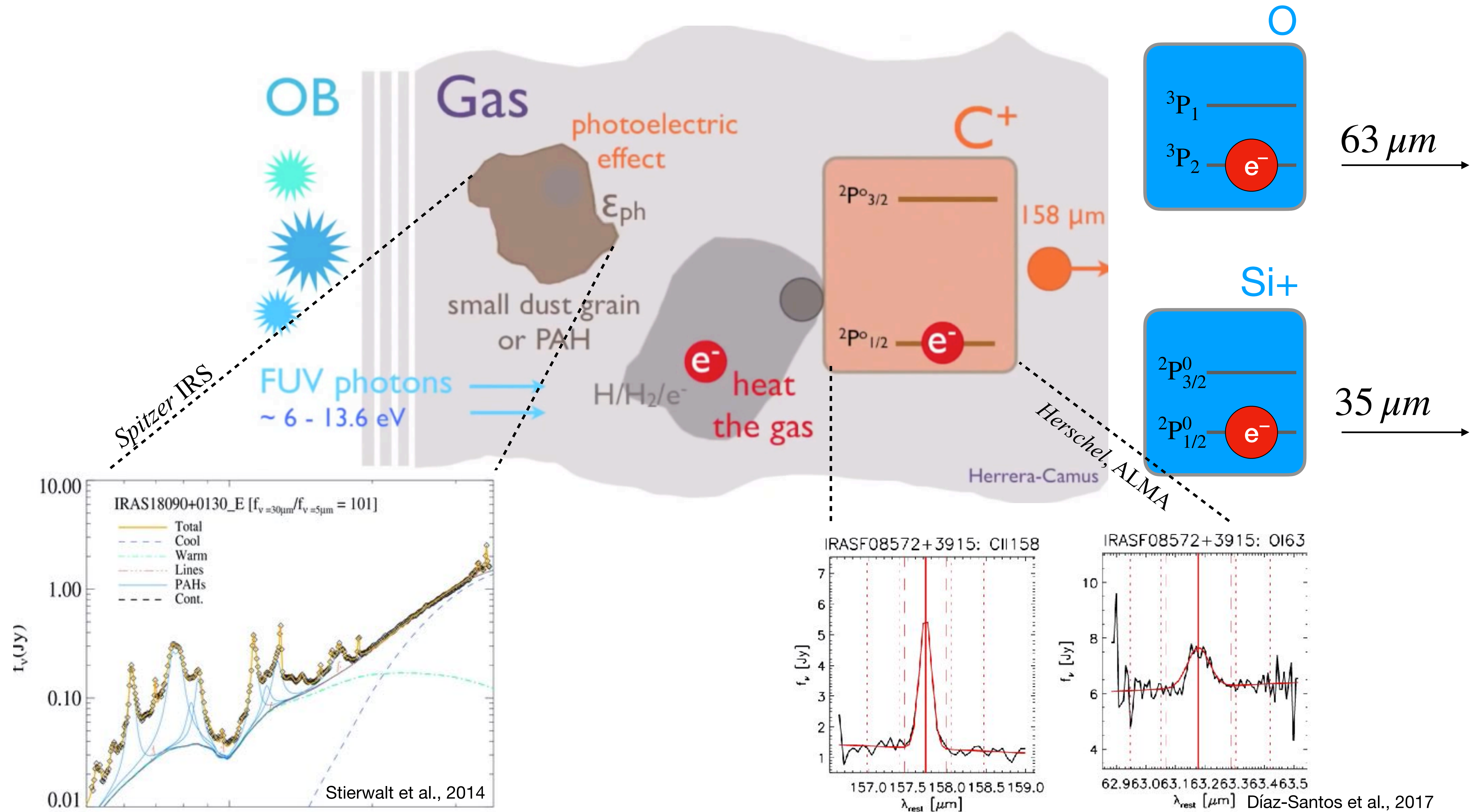
Orion, NASA JPL/Caltech



COOLING – FAR IR LINES, [C II]

- ▶ PAHs transfer energy from stars into the ISM
- ▶ That gas then needs to cool to form stars.
- ▶ Most of the cooling comes in the form of far-IR atomic line emission: [C II], [O I], [Si II]





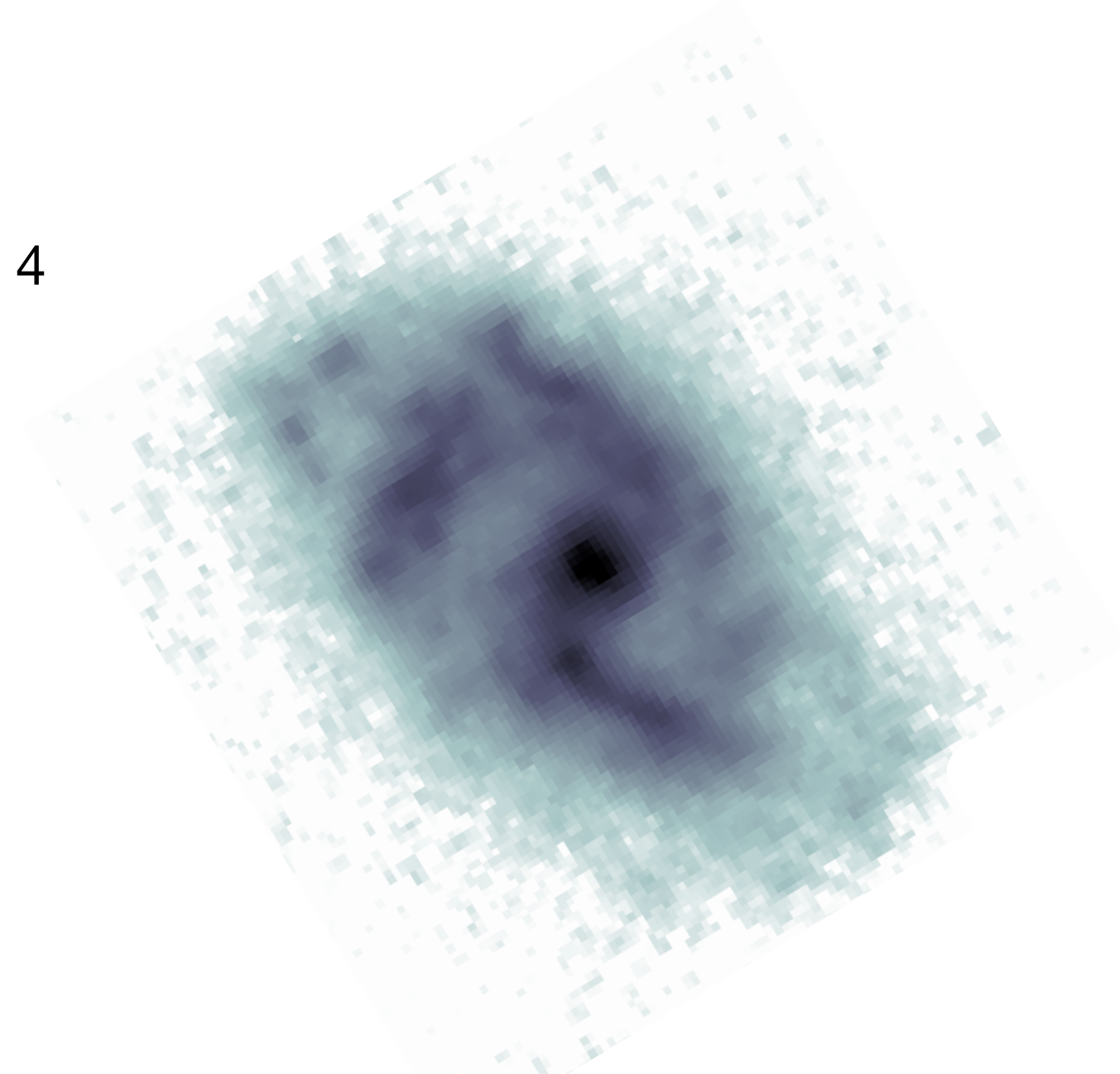
Vibrational emission lines in the mid-IR

Fine-structure lines in the mid- and far-IR

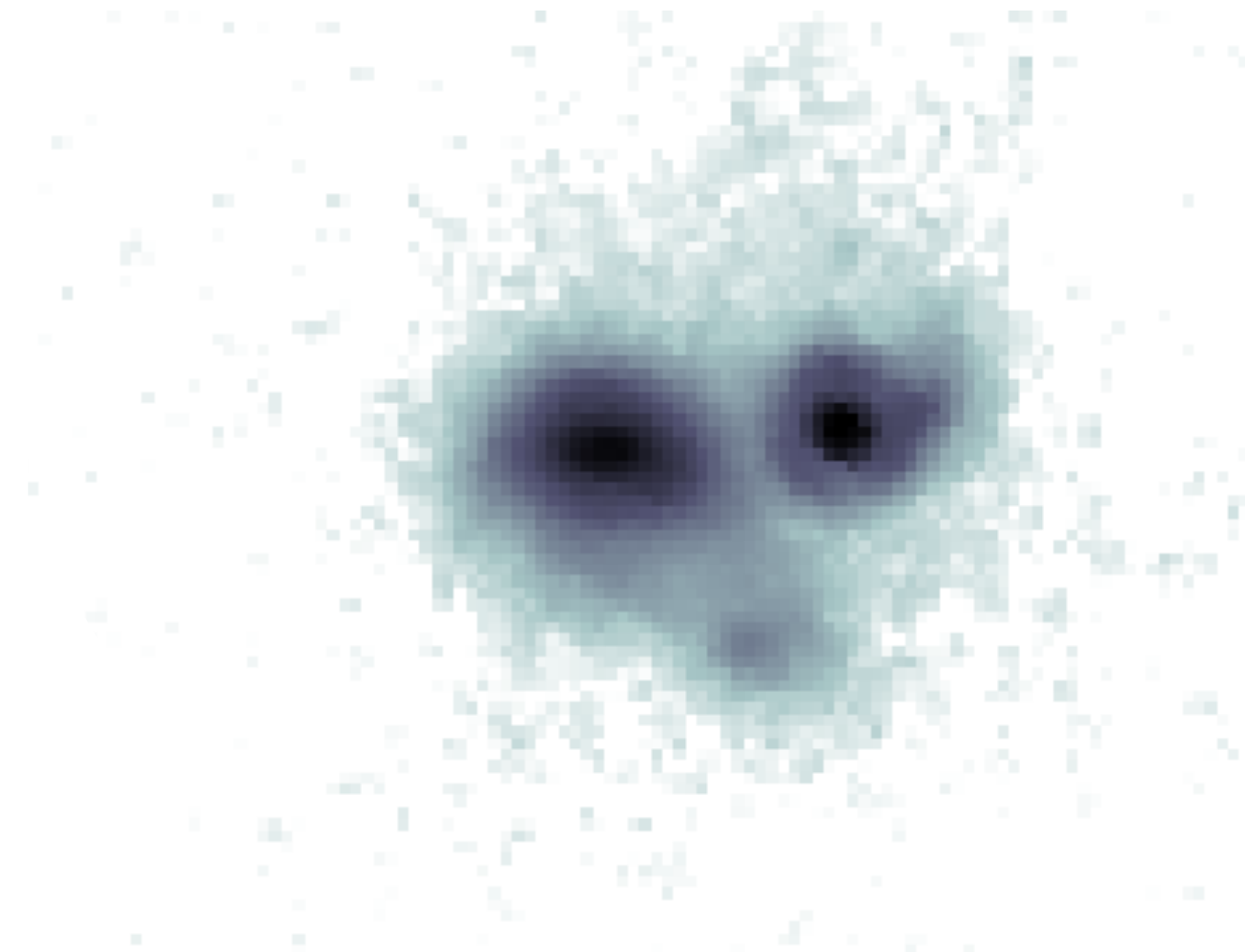
MEASURING HEATING AND COOLING IN THE MOST EXTREME DUSTY GALAXIES TODAY

- ▶ The **Great Observatories All-Sky LIRG Survey** (GOALS, Armus et al., 2009) is a complete sample of IR-luminous galaxies in the local Universe, and reaches some of the extreme conditions that are more typical at cosmic noon.

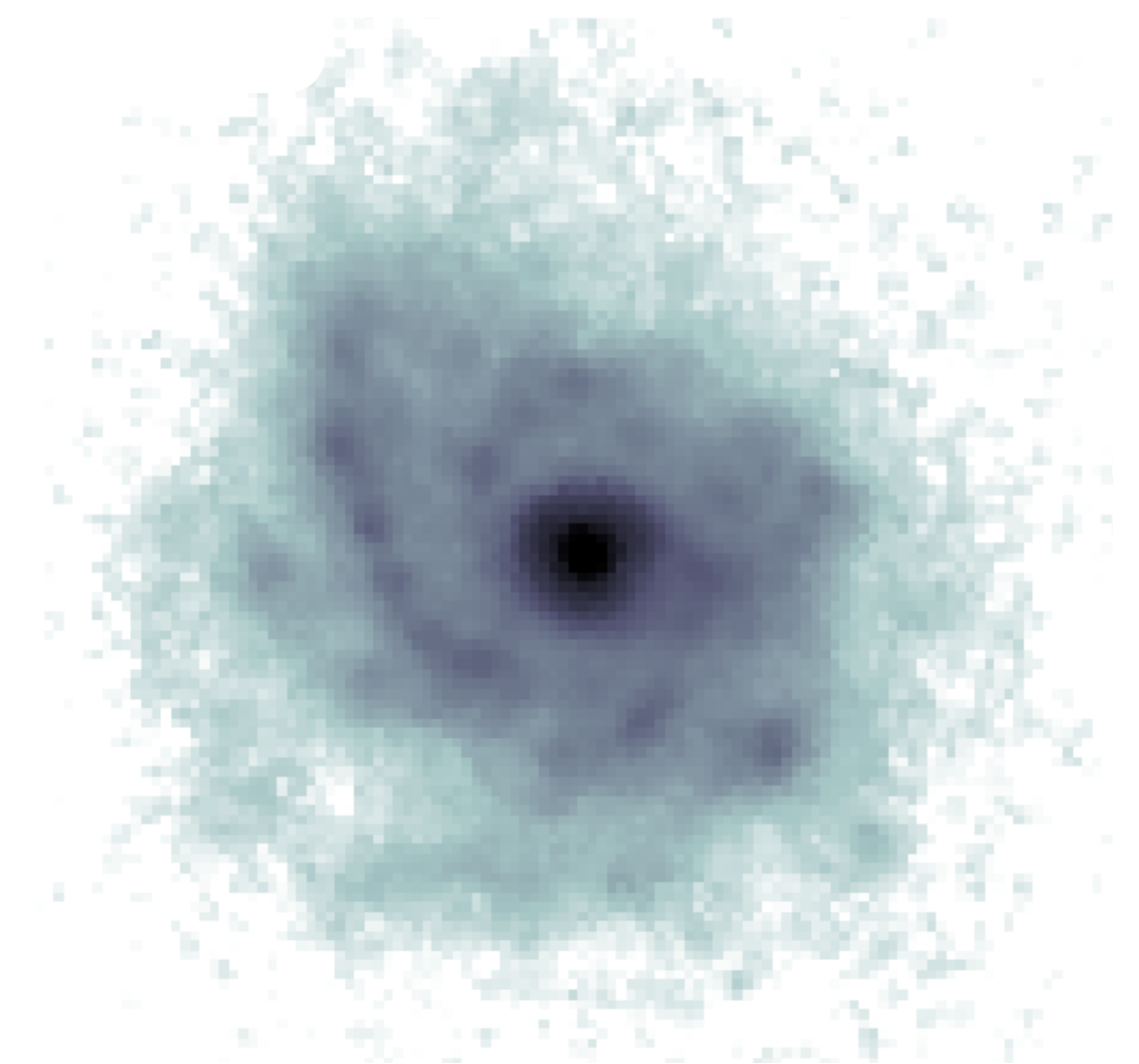
IRAC Ch. 4



ESO221-IG010



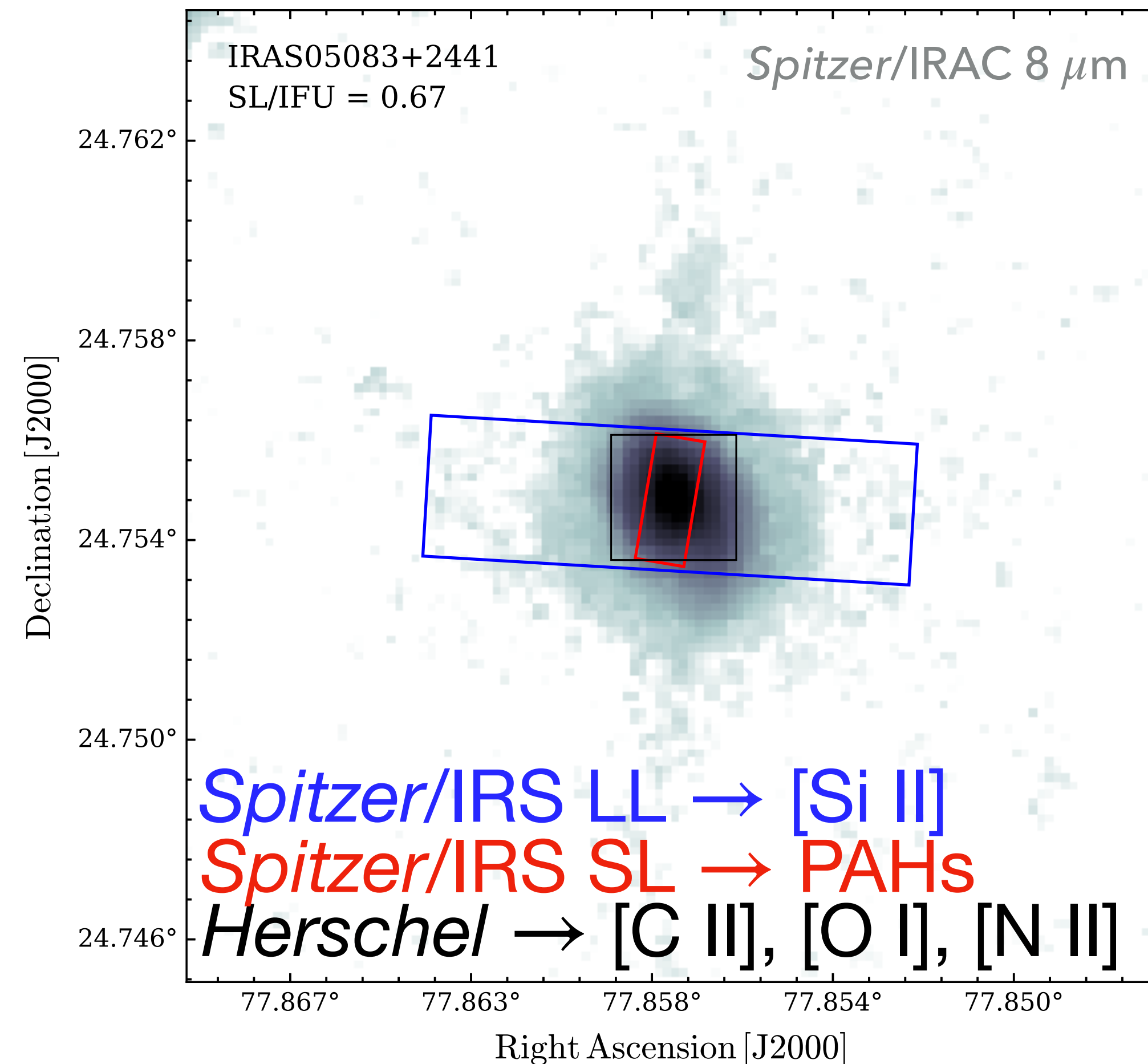
NGC 7592



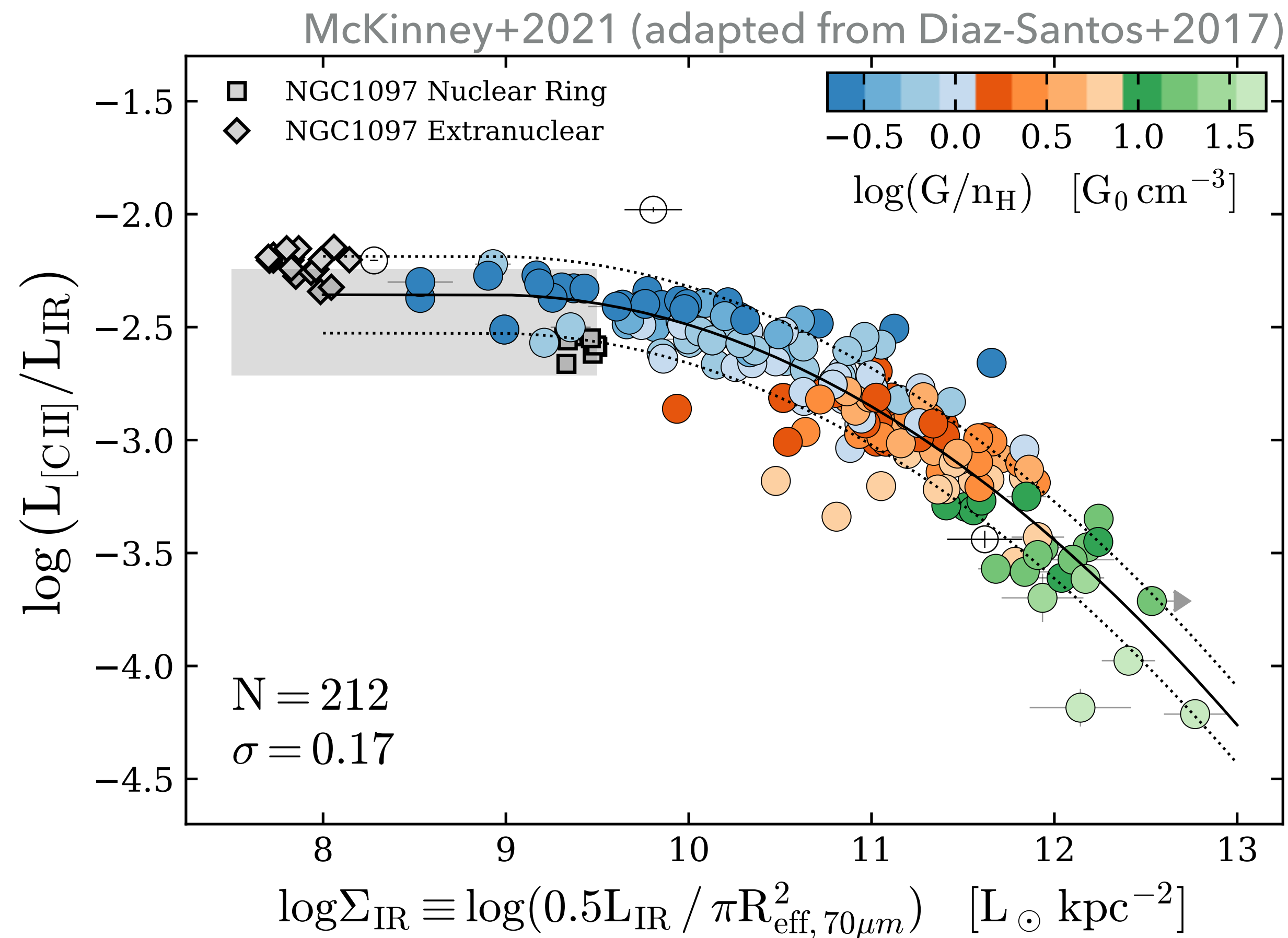
NGC 5936

GOALS – A COMPLETE SURVEY OF LOCAL IR-LUMINOUS GALAXIES

- ▶ 202 systems, 244 galaxy nuclei
- ▶ High mass, $Z/Z_{\odot} \sim 1 - 2$
- ▶ Spectral coverage across the EM spectrum measuring many properties of the ISM
 - ▶ *Spitzer* → PAHs, mid-IR AGN fractions, mid-IR opacities
 - ▶ *Herschel* → far-IR cooling lines, gas densities, radiation field strengths

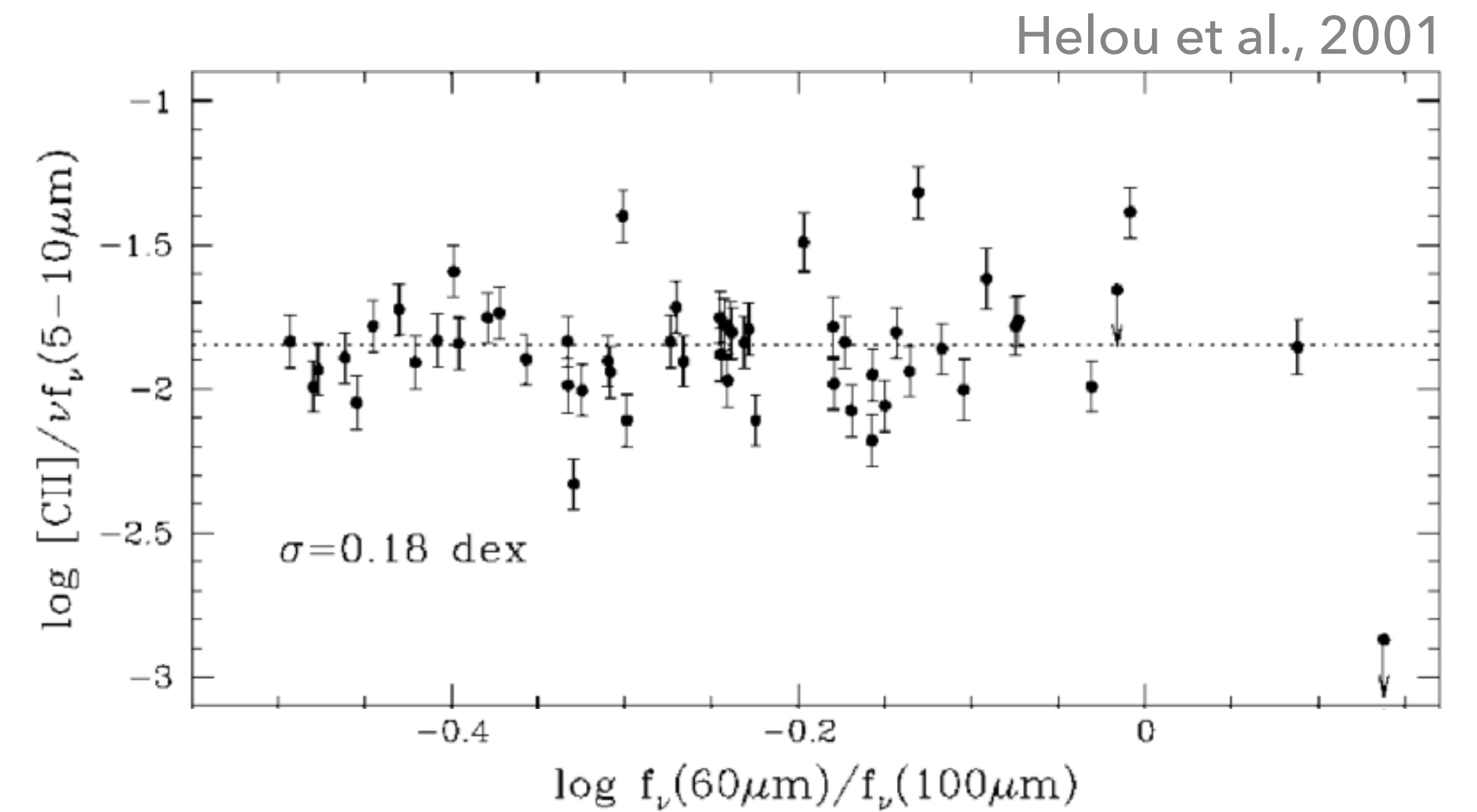
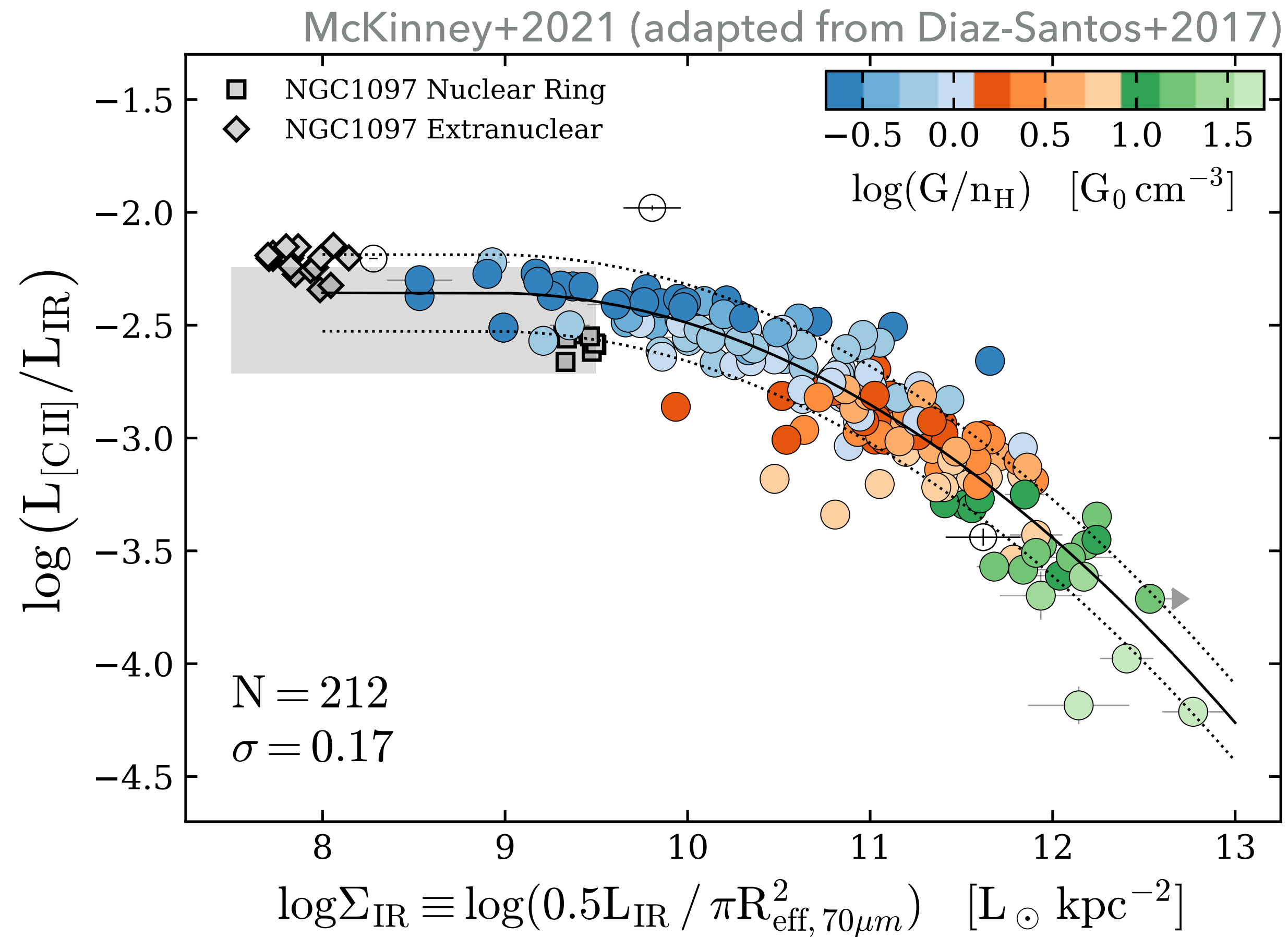


THE COOLING DEFICIT



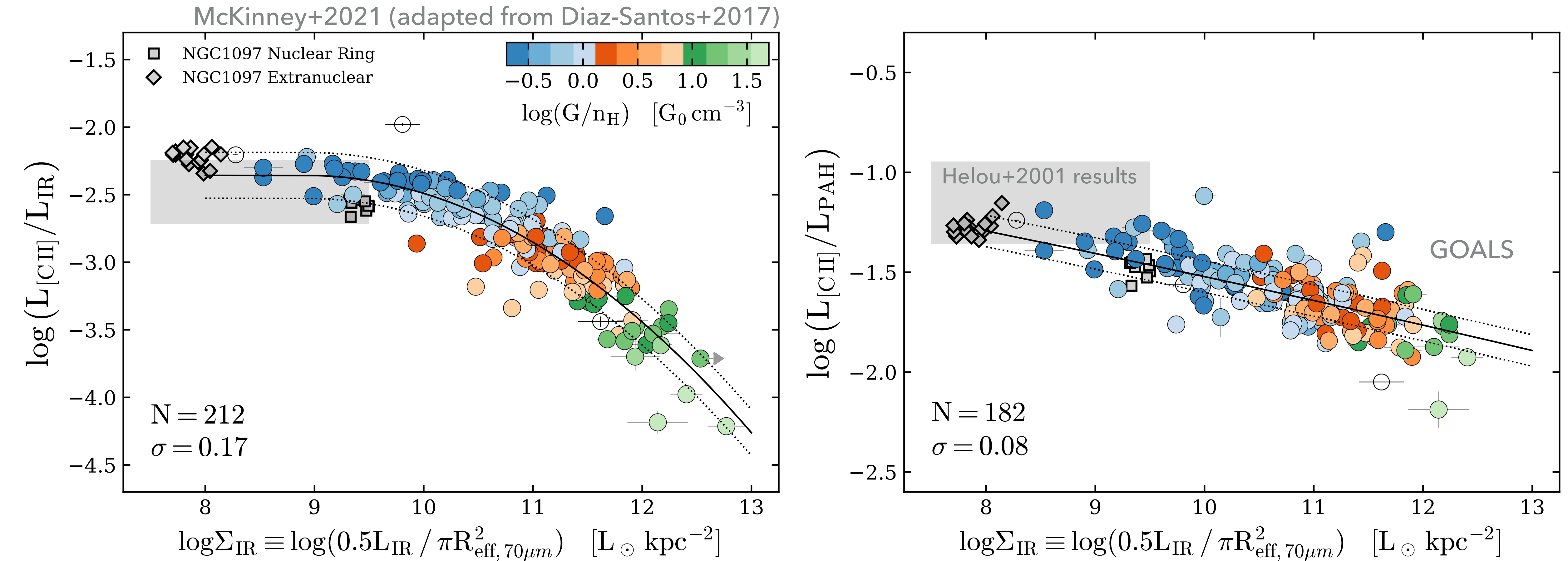
- ▶ The brightest, most compact LIRGs emit less power in cooling lines relative to $L(\text{IR})$.
- ▶ This deficit is observed at high redshift, and for PAH emission as well.

THE COOLING DEFICIT



Early observations suggest the cooling/heating ratio is a constant in star-forming galaxies.

THE COOLING TO HEATING RATIO: [C II] VS. PAH

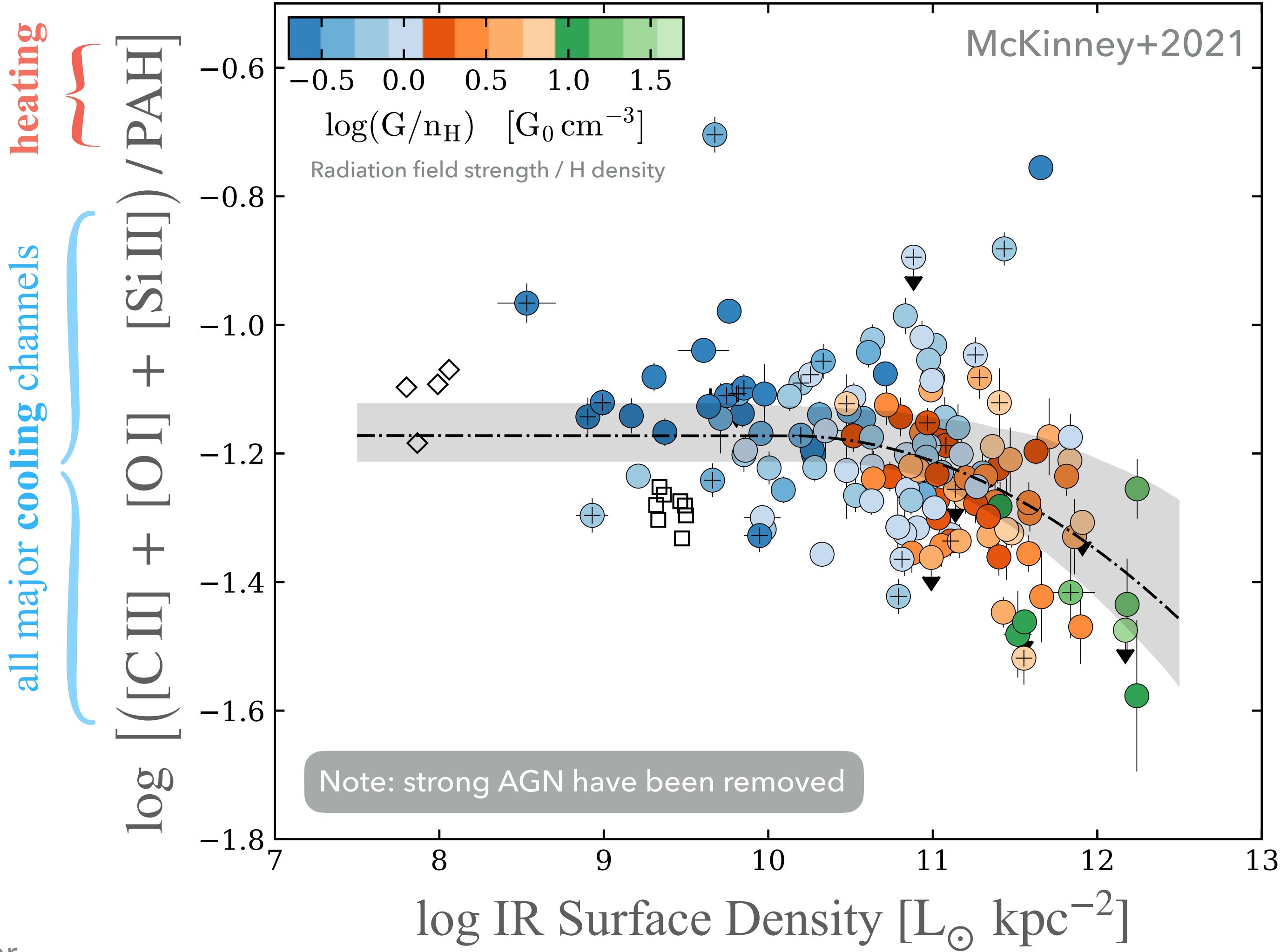


THE COOLING TO HEATING RATIO: [C II]+[O I]+[Si II] VS. PAH, AND THE PHOTOELECTRIC EFFICIENCY

Definition

The cooling/PAH ratio measures the photoelectric efficiency (ϵ_{pe}): the fraction of energy absorbed by PAHs that gets transferred into the gas.

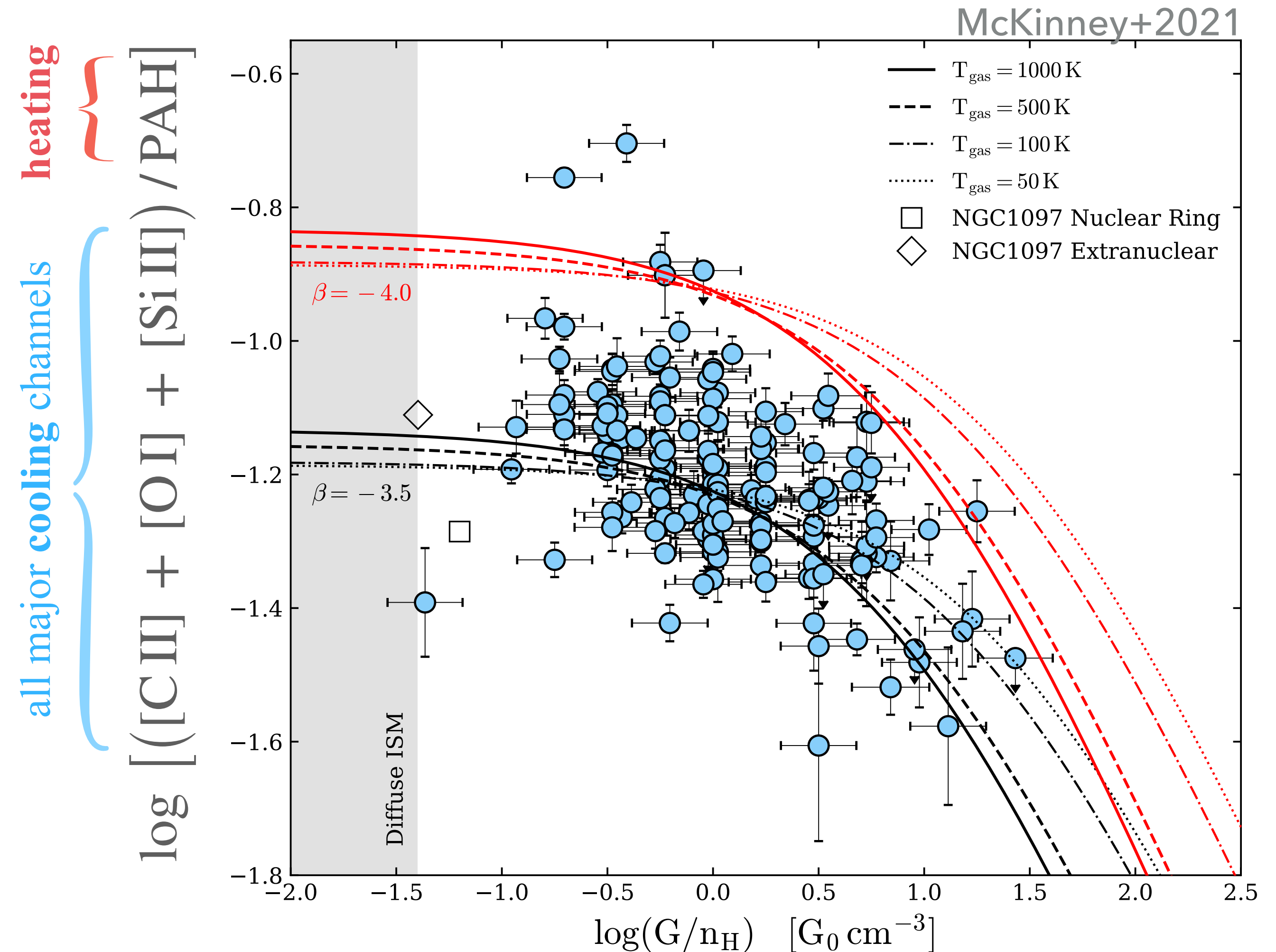
$$\epsilon_{pe} \sim \frac{[\text{C II}] + [\text{O I}] + [\text{Si II}] + \dots}{\text{PAH}}$$



WHAT LOWERS THE PHOTOELECTRIC EFFICIENCY?

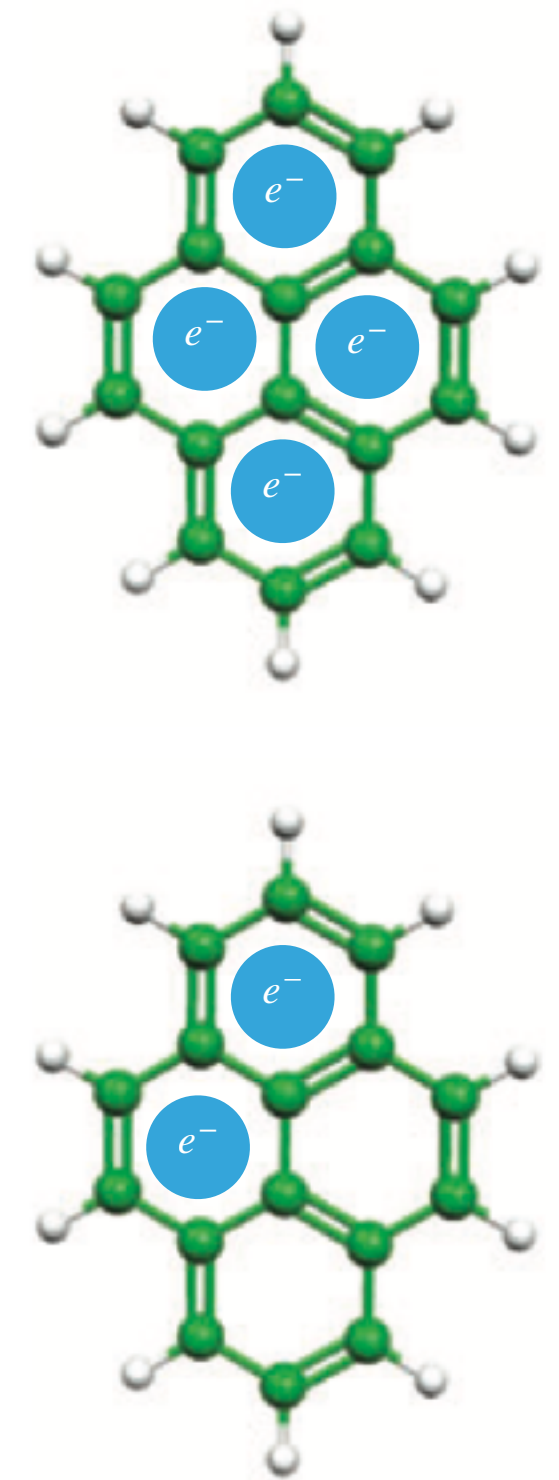
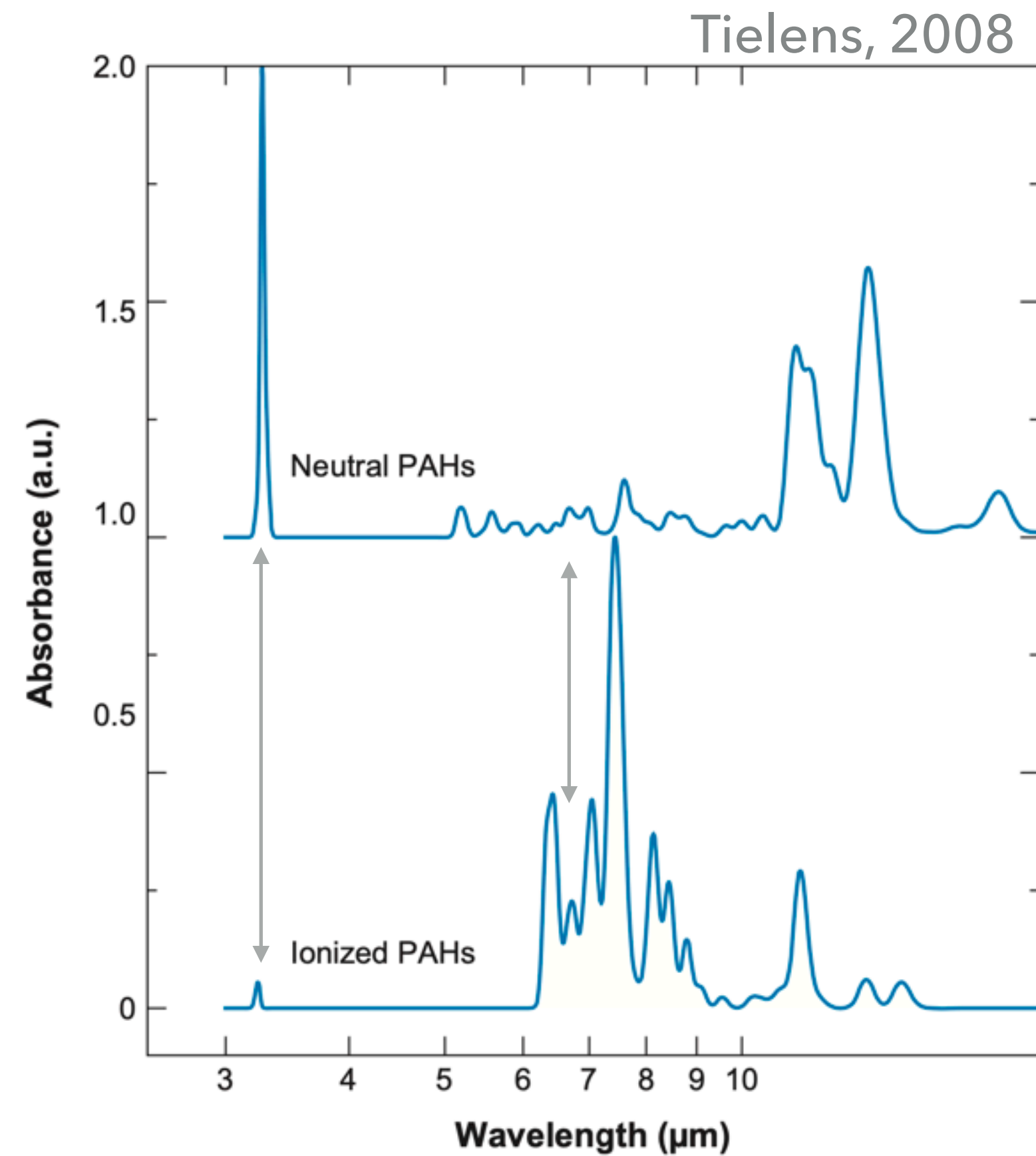
- ▶ Models of PAH grains show low photoelectric efficiencies when:

- ▶ 1) G/n_H is large
- ▶ 2) T_{gas} is high
- ▶ 3) PAHs are larger

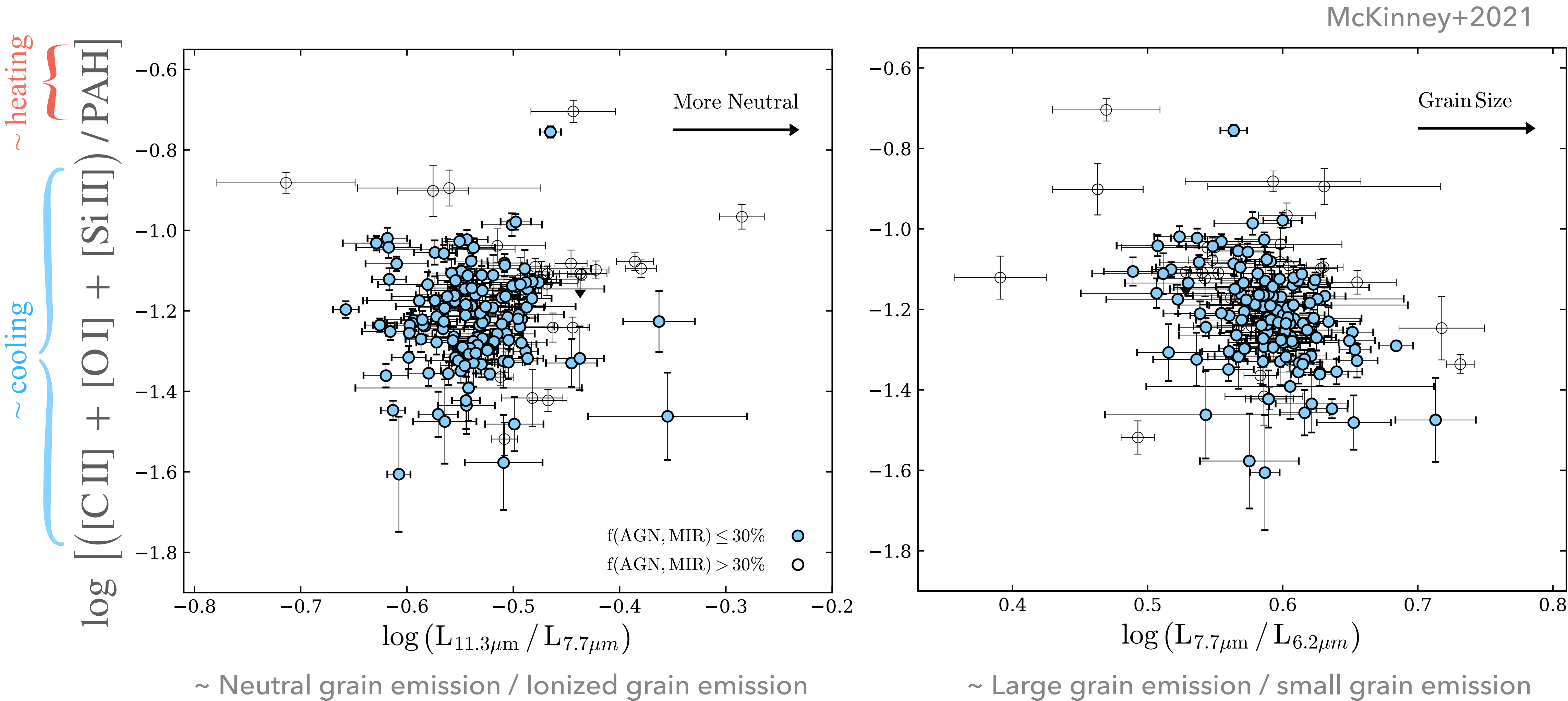


PAH LINES TRACE THE PROPERTIES OF DUST

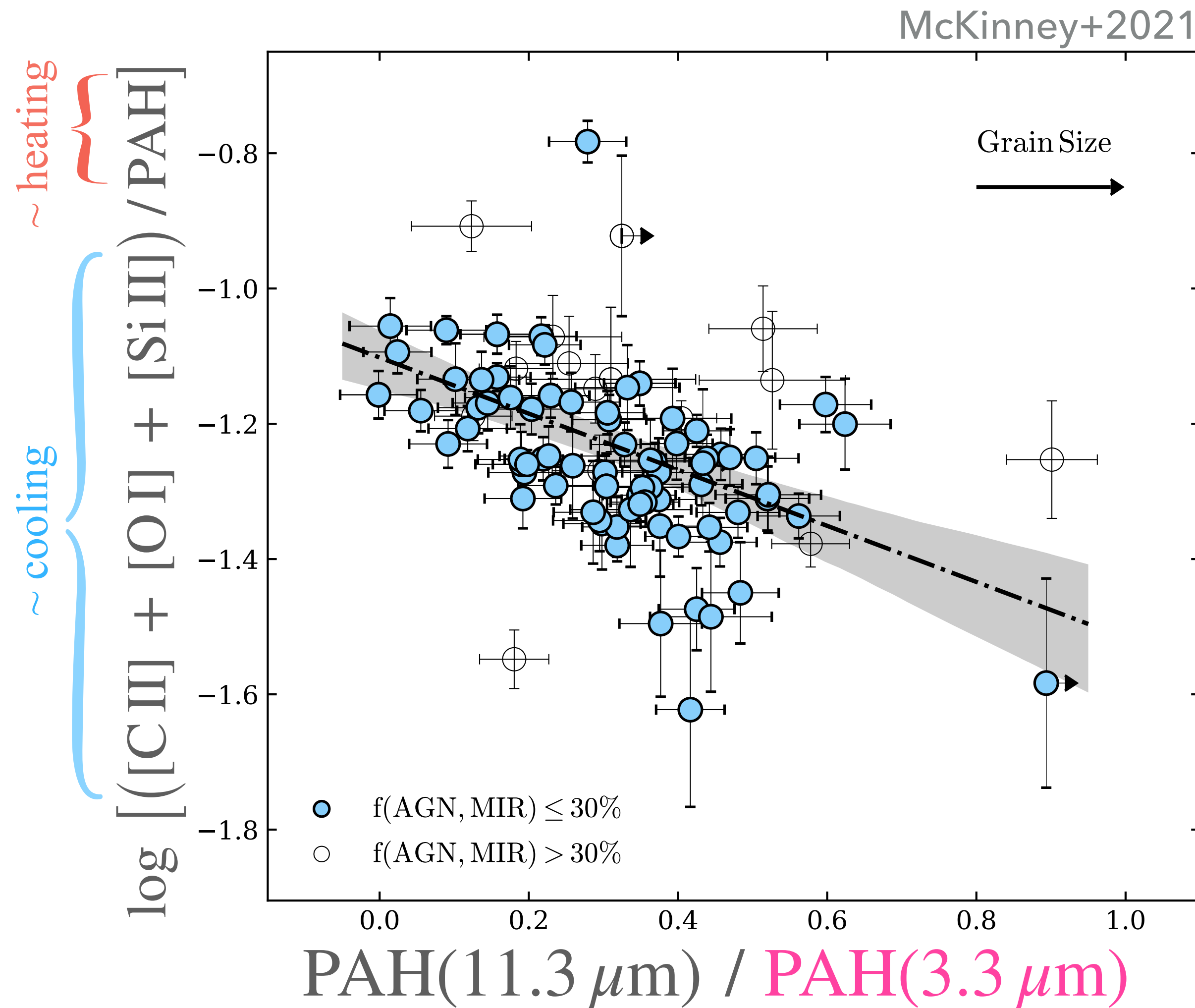
- ▶ Individual PAH emission lines trace the physical properties of small dust grains.
- ▶ Ionized PAHs, and large PAHs have low photoelectric efficiencies.



PAH LINES TRACE THE PROPERTIES OF DUST

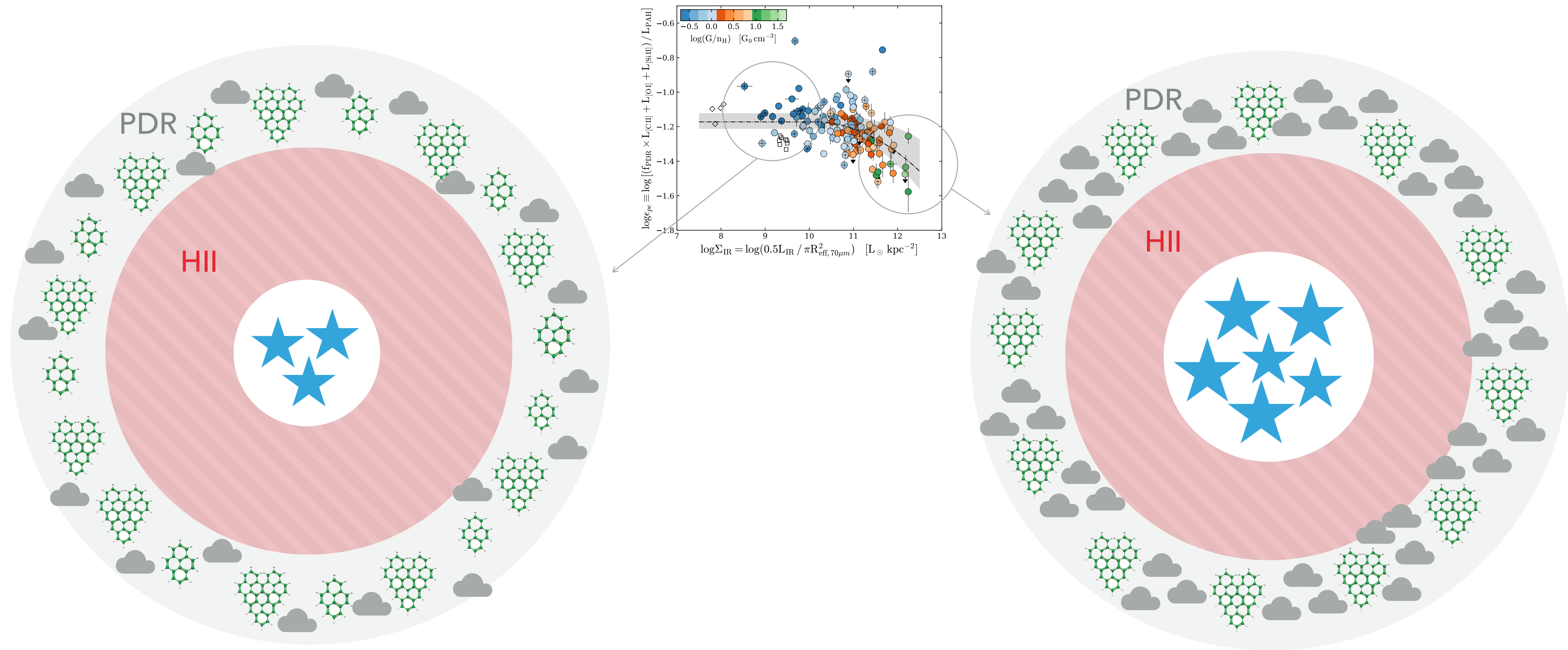


PAH LINES TRACE THE PROPERTIES OF DUST



- ▶ Best constraint on PAH grain size from lines with large wavelength separation.
- ▶ $3.3 \mu\text{m}$ PAH outside of *Spitzer's* coverage, measurable with AKARI
- ▶ **JWST/MIRI** can measure the $3.3 \mu\text{m}$ PAH out to $z \sim 2 - 6$, cosmic noon.

A UNIFIED PICTURE: TYPICAL ISM CONDITIONS AROUND STAR-FORMING REGIONS IN COMPACT LIRGS



Low IR surface densities - "more normal conditions"

- Normal radiation fields
- Large + small grains
- $\epsilon_{pe} \sim 0.08$

High IR surface densities - "extreme conditions"

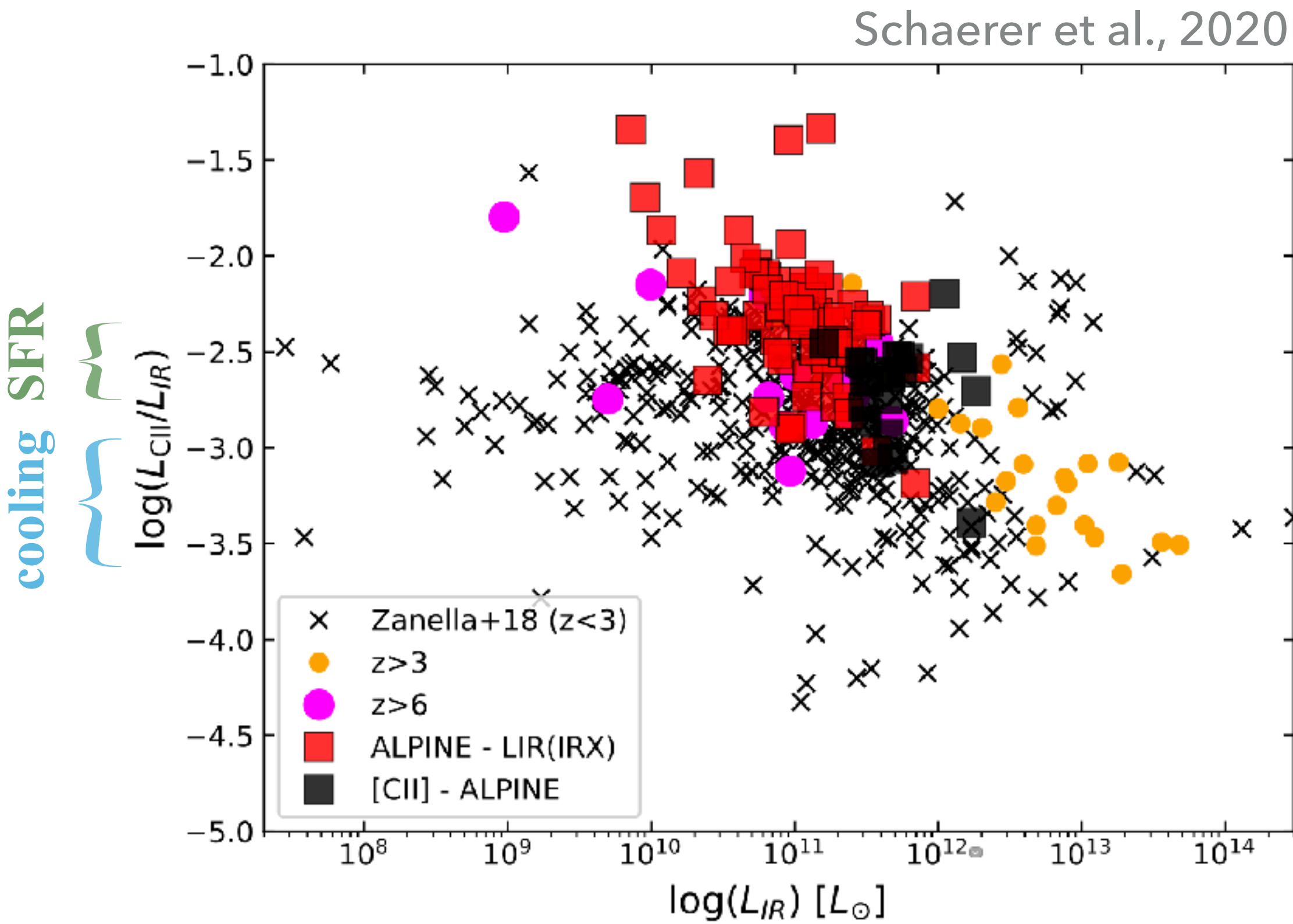
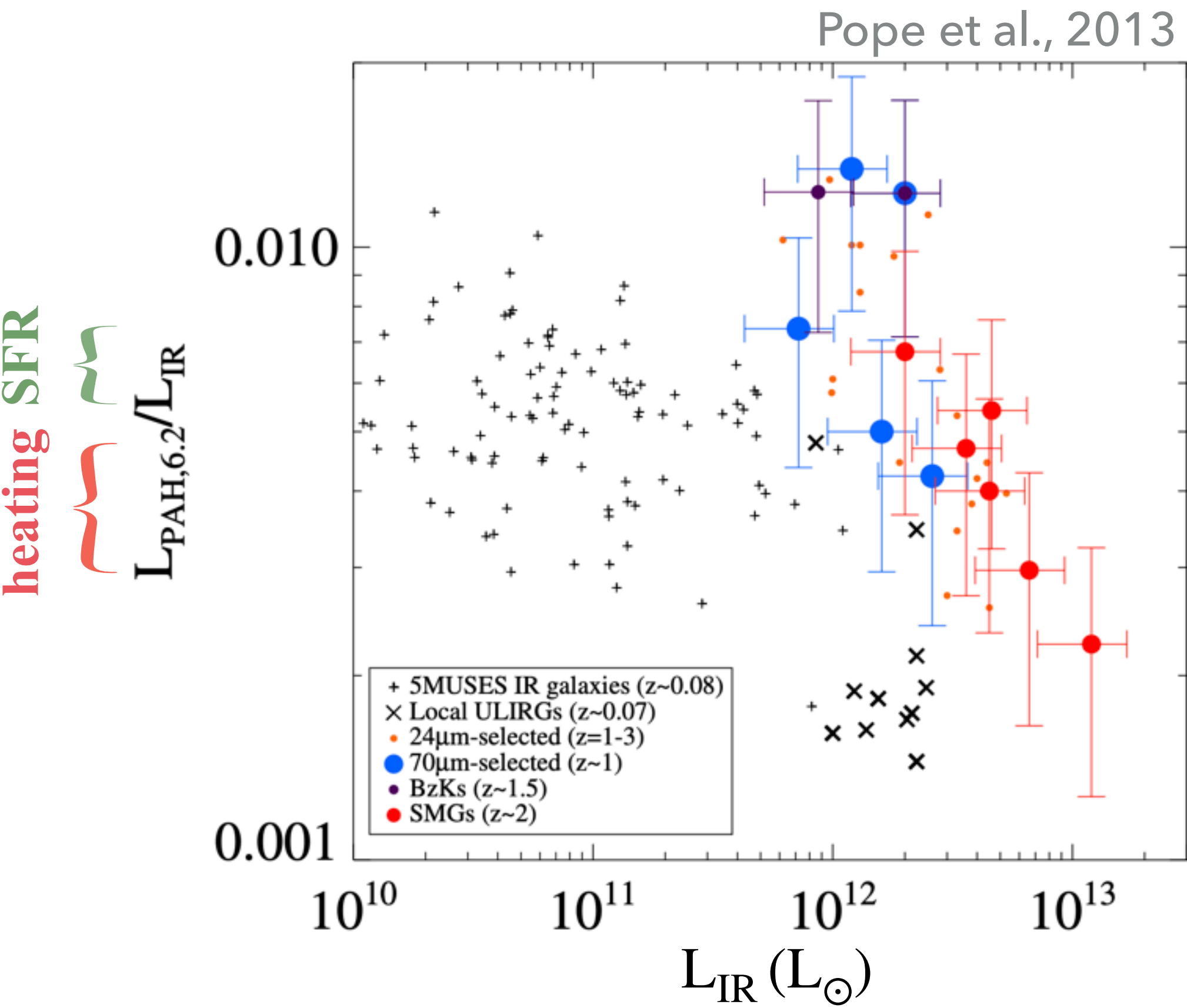
- Strong radiation fields. Dusty, compact, and young
- Small grains less dominant - larger grains important
- $\epsilon_{pe} \sim 0.03$

SUMMARY SO FAR

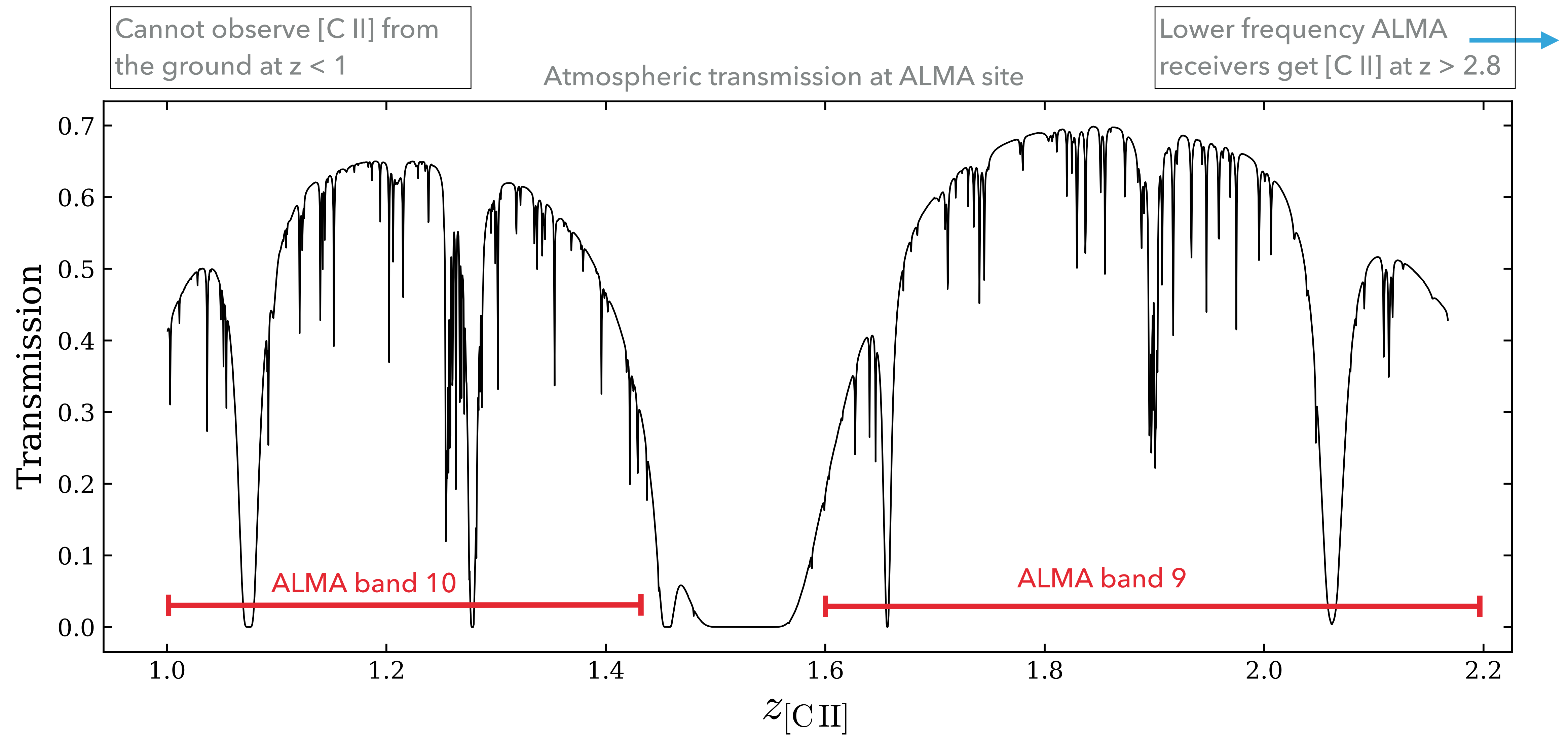
1. Low cooling/heating (\sim photoelectric efficiency, ϵ_{pe}) at high IR surface density
2. Low photoelectric efficiencies arise when the radiation field strength is high
3. Strong radiation fields re-configure the dust grain properties in ways that diminish the transfer of energy from stellar photons into the ions (i.e., C+)

Are such ISM conditions also found in high-redshift star-forming galaxies?

HIGH-Z OBSERVATIONS OF THE ISM: PAHS AND COOLING LINES

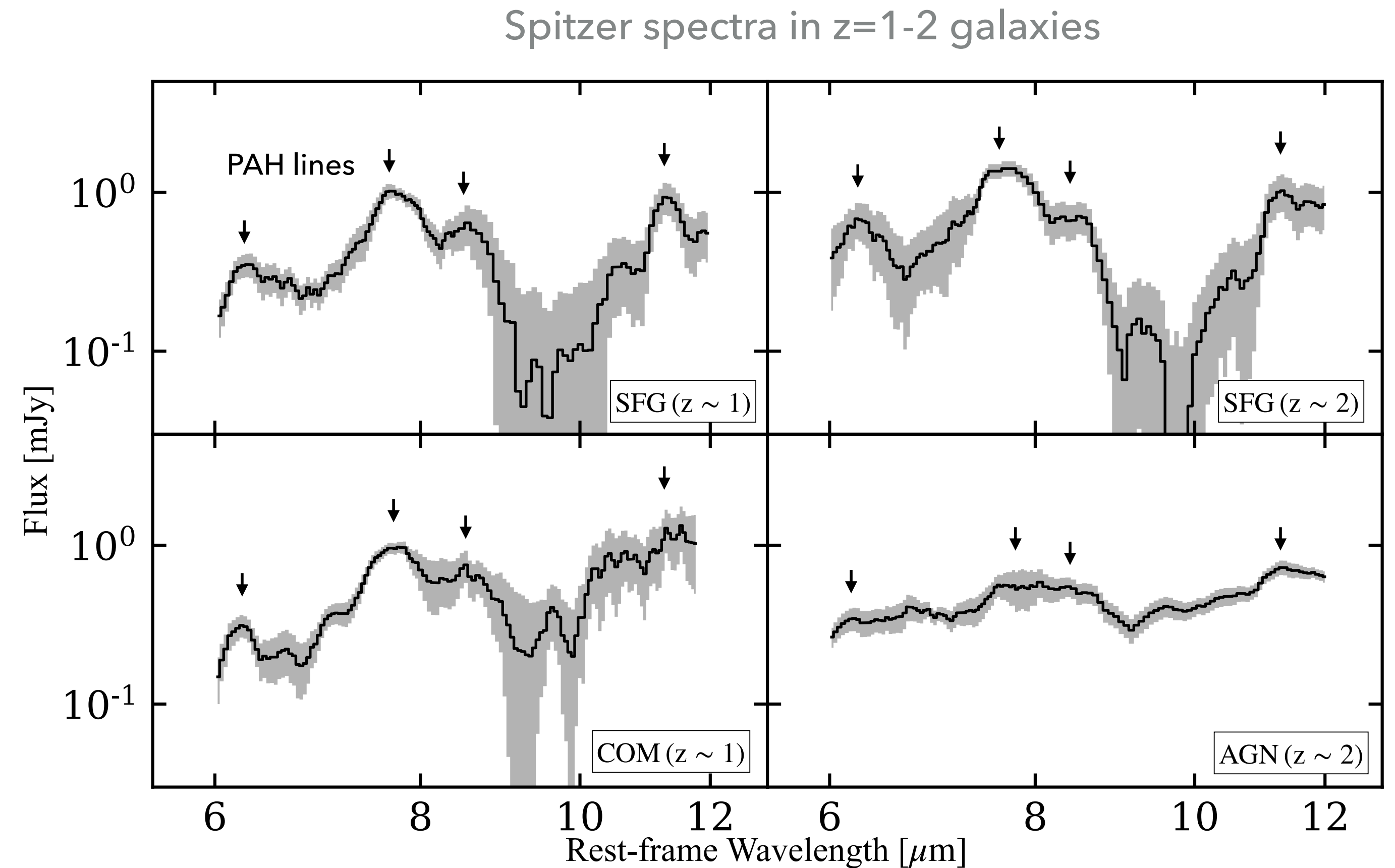


HEATING AND COOLING IN THE ISM OF HIGH REDSHIFT DUSTY GALAXIES

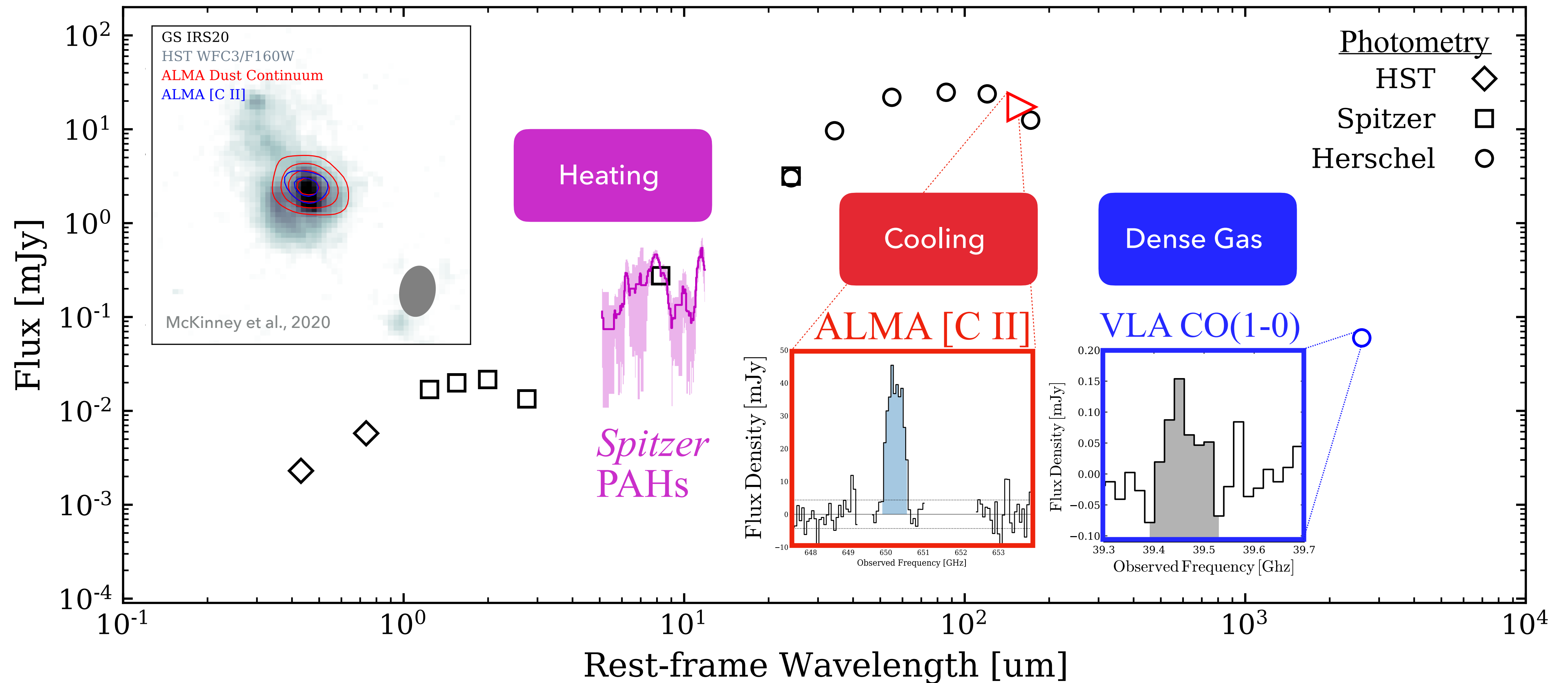


HIGH REDSHIFT OBSERVING STRATEGY

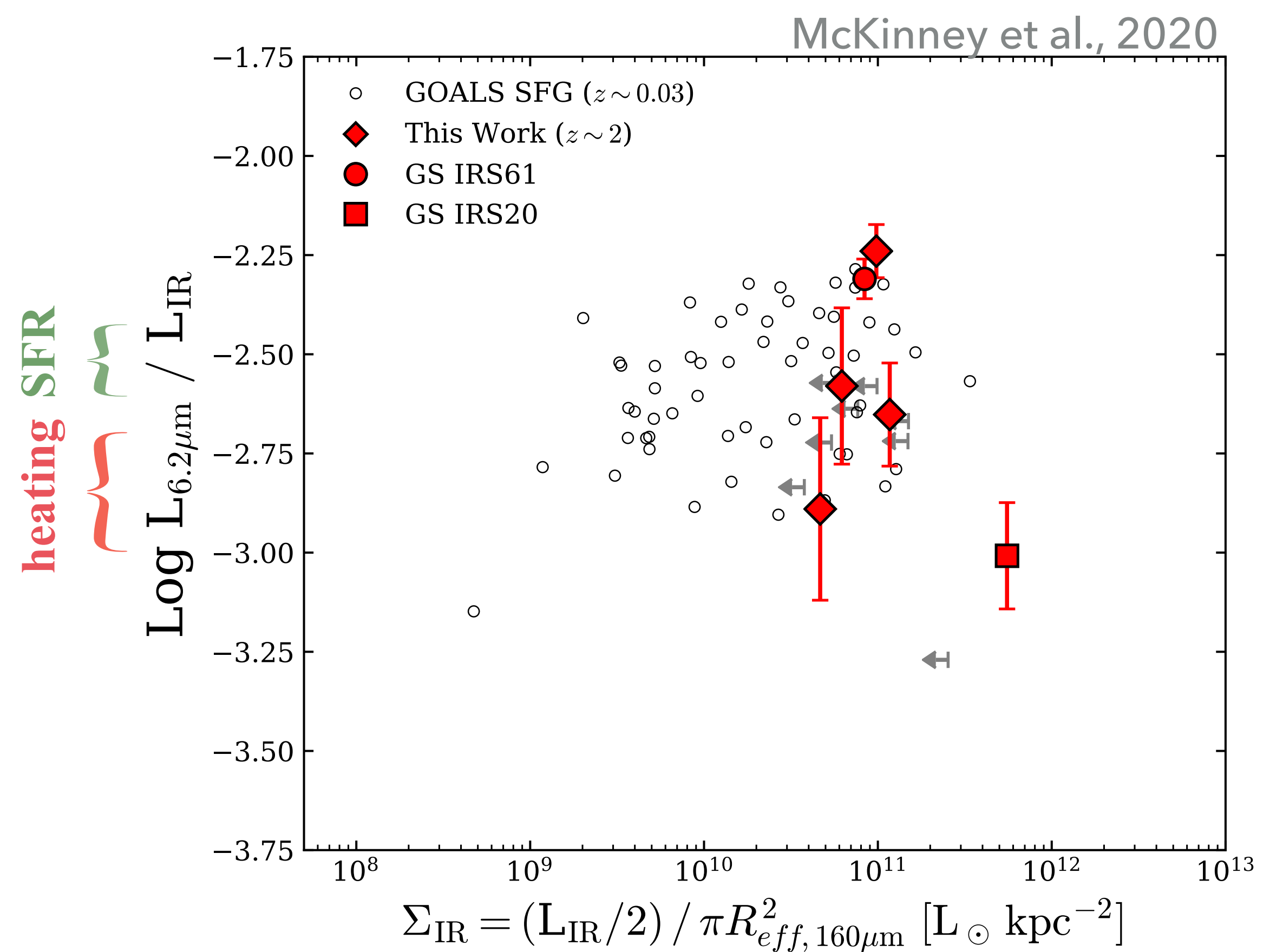
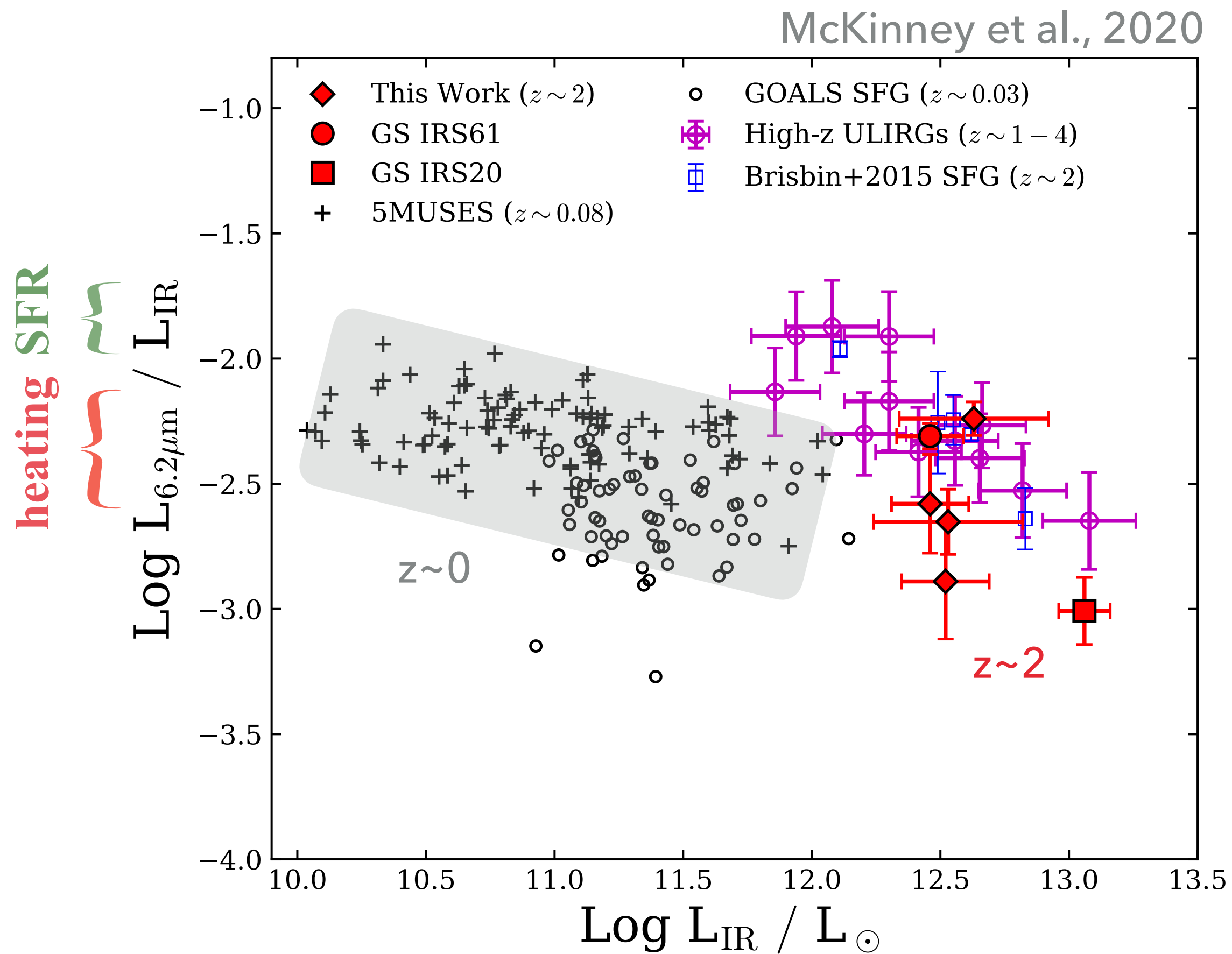
- ▶ Testing heating/cooling at $z=2$ must work from archival Spitzer spectra of PAHs until JWST
- ▶ High mass, high metallicity, (\sim GOALS)
- ▶ ALMA follow up can get [C II]
- ▶ Other cooling lines (e.g., [O I]) will need a cryogenically cooled space telescope to observe at high- z



A SPITZER-SELECTED SAMPLE OF Z=2 LIRGS WITH ALMA FOLLOW UP

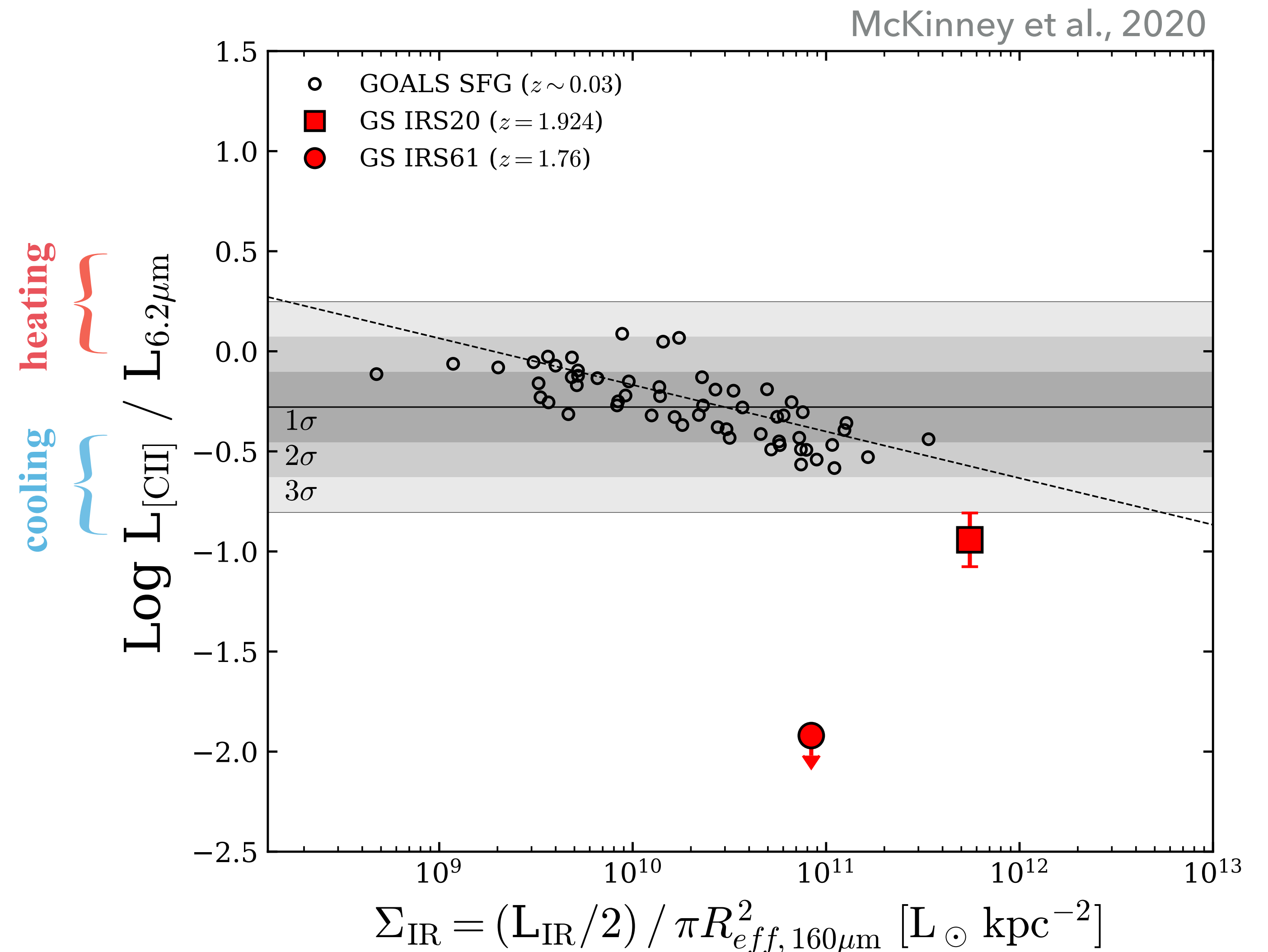


COMPARABLE PAH EMISSION FOR FIXED IR SURFACE DENSITY



THE PHOTOELECTRIC EFFICIENCY AT COSMIC NOON

- ▶ Cosmic noon compact LIRGs have low [C II]/PAH ratios
- ▶ More [O I] cooling, or low photoelectric efficiencies?



NEXT STEPS: ISM CONDITIONS OVER COSMIC TIME

- ▶ Is there a link between ϵ_{pe} and the efficiency of star-formation? Does this evolve with redshift?
- ▶ Upcoming work:
 - ▶ CO observations of GOALS to link ϵ_{pe} and SFE at $z=0$
 - ▶ VLA CO observations of cosmic noon galaxies with [C II] and PAHs

